**Stream Channel Response to Peak Flows in a Fifth-Order Mountain Watershed**

by

John M. Faustini

A DISSERTATION

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Doctor of Philosophy

Presented April 27, 2000
Commencement June 2001

# AN ABSTRACT FOR THE DISSERTATION OF

John M. Faustini for the degree of Doctor of Philosophy in Geology presented on April 27, 2000. Title: Stream Channel Response to Peak Flows in a Fifth-Order Mountain Watershed.

Abstract Approved: _____

Julia Allen Jones

This investigation explored how the magnitude, style, and frequency of channel adjustments vary spatially and over time within a 5th-order mountain watershed. Historical data sets, including repeated cross section surveys spanning up to 20 years at five sites on 2nd to 5th-order channels and streamflow records spanning up to 50 years, were supplemented by mapping and field reconnaissance activities.

The study had two major parts. The first focused on two adjacent, contrasting stream reaches to examine the influence of large woody debris (LWD) on channel morphology and channel response to peak flows in a 3rd-order stream. The upper reach flows through old-growth forest with abundant LWD, while the lower reach was clearcut in 1964-65 and contains little LWD. A 25-year flood in 1996 caused deposition upstream of LWD steps in the old-growth reach alternating with scour between steps, resulting in no net gain or loss of sediment within the reach, while extensive scour and coarsening of the bed occurred in the clearcut reach. These observations suggest that reach-scale channel response was strongly influenced by LWD abundance, but that response at finer scales depends critically on the details of the location and arrangement of LWD.

The second part of the study examined the dynamics of channel response to peak flows over two decades, and to two particular large floods during that period, in different portions of the channel network. The cross section data show that the streambed at the study sites is very stable, particularly in lower-order channels. Peak

flows that produced detectable change at 90% of cross sections—flows able to cause significant channel adjustments—recur approximately three times as frequently (every 6-7 years) in $4^{th}$ to $5^{th}$-order Lookout Creek as in $3^{rd}$-order Mack Creek (20-25 years). Flows that produced detectable change at 25% of cross sections are estimated to occur on average every 1.7 to 3.0 years at the study sites. It is estimated that if peak flows of all sizes were increased by only 10% due to anthropogenic impacts (e.g., logging) or climate change, the frequency of peak flows of a magnitude observed to produce significant channel adjustments would increase by approximately 30% in Lookout Creek and 60% in Mack Creek.

Stream Channel Response to Peak Flows in a Fifth-Order Mountain Watershed

by

John M. Faustini

A DISSERTATION

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Doctor of Philosophy
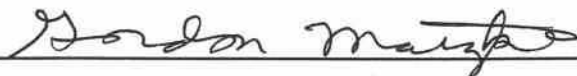
Presented April 27, 2000
Commencement June 2001

Doctor of Philosophy dissertation of <u>John M. Faustini</u> presented on <u>April 27. 2000</u>
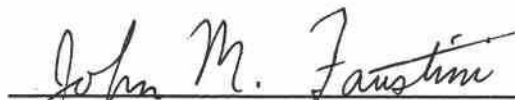
APPROVED:

_____

Major Professor, representing Geology


_____

Chair of the Department of Geosciences


_____

Dean of the Graduate School


I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.


_____

John M. Faustini, Author

# Acknowledgements

This dissertation marks the culmination of a learning experience that for me has been occasionally exhilarating, often trying, and ultimately very rewarding. It could not have happened without the help of a large number of people along the way.

First I would like to thank the members of my Doctoral Committee who provided guidance and support during my graduate work. Gordon Grant got me excited about mountain streams and floods, and kept me on my toes with his probing questions and insightful comments. Stan Gregory introduced me to the ecological aspects of streams, provided helpful historical background information on Mack Creek (as well as access to his Mack Creek wood data), and was responsible for a very memorable winter field trip for Stream Ecology which included a bonus lesson in the physics of frictionless surfaces. Roy Haggerty and Bruce McCune served as willing and engaged committee members. Fred Swanson acted as an unofficial co-advisor, and I thank him for his intellectual enthusiasm and his encouragement to think about the "big picture," as well as for coming up with funding to keep me going after my graduate traineeship ran out.

Julia Jones served not just as an advisor, but as mentor and guide through the intellectually challenging and sometimes emotionally turbulent process of completing a Ph.D. program. I am forever grateful for her unwavering support and confidence in me, and for her remarkable ability to always come up with a helpful suggestion to get me started again when I got stuck.

I was fortunate to have two excellent field assistants—Greg Finch for the 1997 field season and Carl Jahn for the 1998 season—who both provided conversation, companionship, and very capable and reliable assistance in the field, sometimes under less than ideal weather conditions. I owe them both a debt of thanks for their diligence and positive attitude through all the difficulties.

Many other people provided assistance with field equipment, field work, or data. In particular, I received a great deal of assistance from folks at the U.S. Forest Service (USFS) Forestry Research Laboratory in Corvallis, Oregon. I thank Craig Creel for providing access to surveying equipment that was crucial to my field work,

# Table of Contents

**Table of Contents (continued)**

## Table of Contents (continued)

# List of Figures

# List of Figures (continued)

## List of Figures (continued)

# List of Figures (continued)

# List of Tables

## List of Tables (continued)

# List of Appendices

# List of Appendix Figures

## List of Appendix Figures (continued)

# List of Appendix Tables

# Preface

The theme of this dissertation is stream channel response to peak flows in mountain watersheds. Unlike their better-studied lowland counterparts, which in their natural state are shaped almost entirely by fluvial processes, mountain streams are strongly influenced by external landforms and processes that interact with and constrain the fluvial processes operating within the stream channel. While large low-gradient floodplain rivers are typically able to significantly rework their channels on a nearly annual basis, in high-gradient mountain streams the presence of bedrock, coarse bed material, and other relatively immobile debris such as large boulders and logs can limit the ability of the stream to reshape its bed except in large, infrequent floods. Within mountain watersheds, spatial variations in geology and natural or anthropogenic disturbance (e.g., fire, logging, etc.) and systematic downstream trends in landscape and channel characteristics (such as slope and channel dimensions relative to the sediment and debris delivered to the stream) combine to created a complex mosaic of spatially varying landscape patterns and processes which influence stream channel response to peak flows. This study investigated how the magnitude, style, and frequency of channel adjustments to peak flows vary spatially and over time within a $5^{th}$-order mountain watershed.

The dissertation consists of two major parts, both of which draw upon historical data sets available at the H.J. Andrews Experimental Forest in the Western Cascades of Oregon, supplemented by additional field investigation by the author. The first half examines the role of large woody debris (LWD) in modifying stream channel structure and its response to a large flood (estimated recurrence interval of approximately 25 years) in February 1996 by comparing channel morphological characteristics and the response of the channel as measured by repeated cross section surveys in two nearly adjacent, contrasting reaches of a $3^{rd}$-order stream within the Andrews Forest. The upper reach flows through an old-growth Douglas-fir/Western Hemlock forest and contains abundant LWD, including several channel-spanning LWD accumulations. The lower reach, located immediately downstream, was clearcut

in 1964-65 and contains very little LWD.  The availability of pre- and post-flood cross section, LWD inventory, and bed material particle size data made it possible to treat the February 1996 flood as a fortuitous "experiment" to test hypotheses about how LWD influences channel response to floods at the reach to within-reach scales.

The second half of the dissertation examines channel response to a wide range peak flows over a larger spatial and temporal scale.  It draws on up to 50 years of streamflow data and 20 years of quasi-annual cross section monitoring data to explore the dynamics of stream channel response to peak flows at five $2^{nd}$ to $5^{th}$-order stream reaches within the 64-km$^2$ Andrews Forest.  This unique data set provided an opportunity to evaluate how frequency of channel adjustment and the relationship between peak flow magnitude and channel response vary between streams of different order within a single watershed in which both the natural history and land management activities have been well documented.  This part of the study examined watershed scale patterns in channel response to peak flows, with particular attention to differences between $2^{nd}$ to $3^{rd}$-order tributaries and $4^{th}$ to $5^{th}$-order "mainstem" channels, in order to test recent hypotheses proposed in the geomorphology literature.

# Stream Channel Response to Peak Flows in a Fifth-Order Mountain Watershed

## Part I. Influence of Large Woody Debris on Channel Morphology and Response to Floods in a Third-Order Stream at the Reach to Within-Reach Scales

## 1    Introduction

Much has been learned in the past 25 years about the importance of large woody debris (LWD) as a geomorphic agent in forested mountain streams. LWD strongly influences channel morphology, regulates sediment storage and transport, and thereby affects the nature, magnitude, frequency and rate of channel change in response to floods and other channel-structuring events (e.g., landslides, debris flows, etc.). This study exploits a unique combination of long-term data sets on channel morphology and on LWD distribution and movement to investigate the interaction between LWD distribution and movement, channel morphology, and channel dynamics in a forested $3^{rd}$-order mountain stream in the Western Cascades of Oregon.

The scale-dependence of the hydraulic, morphologic, and ecological functions of LWD in stream channels has long been recognized (Keller and Swanson, 1979; Marston, 1982; Harmon et al., 1986). This scale dependence leads to a large array of potential LWD influences on channel morphology and process. In their study of a mountain stream system in the Cascade Range of Oregon (which included the stream studied in this investigation), Nakamura and Swanson (1993) found that the effects of LWD on channel morphology and sediment storage changed systematically in moving from small to large channels. For example, LWD caused channel widening in all channels, but the mechanism of widening changed from predominantly sediment accumulation in small ($1^{st}$ to $2^{nd}$-order) channels, to sideslope failure in combination with sediment accumulation in medium ($3^{rd}$ to $4^{th}$-order) channels, to bank erosion in larger ($5^{th}$-order) channels. Similarly, LWD constitutes an important sediment storage control in $1^{st}$ to $5^{th}$-order channels, but relative magnitude and duration of sediment storage associated with LWD is less for larger channels which are able to mobilize

their bed load more frequently and to periodically redistribute LWD within the channel. In general, the amount of LWD (mass per unit channel area) decreases with increasing stream size (Keller and Swanson, 1979; Bilby and Ward, 1991). However, the influence on channel morphology and process is greatest in intermediate-size streams, which are large enough to periodically redistribute much of their LWD load and create channel-spanning accumulations of LWD, finer organic debris, and sediment in structures variously referred to in the literature as debris jams (Keller and Swanson, 1979), debris dams (Bilby, 1981), log steps (Marston, 1982), or coarse woody debris (CWD) jams (Nakamura and Swanson, 1993).

This study examines the influence of LWD on channel morphology and on channel response to a large flood in February 1996 (recurrence interval of approximately 25 years) in two adjacent, contrasting reaches of a single 3$^{rd}$-order stream. The upper reach lies within old-growth conifer forest and contains abundant LWD, including many channel-spanning pieces. The lower reach was clearcut approximately 25 years ago and has almost no LWD within the channel. This strong contrast between the two reaches, in combination with the availability of pre- and post-flood cross section surveys and LWD inventory data, makes it possible to treat the February 1996 flood as a fortuitous, un-replicated experiment. Specific objectives of the study included the following:

1. Characterize differences in channel morphology between the old-growth and clearcut reaches and how these differences are related to differences in the quantity, size, or arrangement of LWD within the channel.

2. Assess differences in channel response to the flood of February 1996 (estimated recurrence interval of approximately 25 years).

3. Make inferences about how LWD modifies channel response to large floods in a steep, 3rd-order stream.

4. Compare the influence of static LWD on channel response to the February 1996 flood with that of LWD that was newly input or was moved during the flood.

The analysis was guided by several specific hypotheses, which include the following:

1.  LWD increases hydraulic roughness and hence decreases flow velocity for a
    given discharge; therefore, LWD promotes channel stability at the reach scale.

2.  At finer scales, LWD creates a diversity of hydraulic environments. Therefore,
    a reach that contains abundant LWD should exhibit greater within-reach spatial
    variability in bed material texture, bed slope, and channel response to a flood
    than a reach with little LWD.

3.  By increasing hydraulic roughness and providing sediment storage sites that
    may be stable even at high flows, channel-spanning LWD accumulations
    increase the sediment storage potential of the channel and decrease bedload
    transport efficiency.

4.  An implication of the preceding claims is that, all else being equal, a reach
    with abundant channel-spanning LWD should exhibit finer bed material
    texture, on average, than a reach with little LWD.

The bases for these hypotheses are discussed further in the following section.

## 2    Literature Review

### 2.1    Influence of LWD on Channel Morphology

The potential influence of LWD on channel morphology and habitat depends on its position with respect to the channel. Robison and Beschta (1990) developed a 4-zone classification of LWD position relative to the channel. In order of decreasing frequency of interaction with flows and generally decreasing significance to channel morphology, the four zones are:

*zone 1*: within the low-flow active channel,

*zone 2*: within the bankfull active channel outside or suspended above low-flow channel,

*zone 3*: suspended above bankfull stage within the bankfull channel width, and

*zone 4*: laterally outside the bankfull channel.

Morphologic influences of LWD can be divided into effects on channel planform, longitudinal profile, and bed material texture. LWD can trigger either abrupt or chronic changes in channel planform and position. Examples of abrupt changes include meander cutoffs or lateral switching of flow into secondary or abandoned channels due to blockage of the main channel (Keller and Swanson, 1979). Chronic changes associated with LWD include accelerated lateral migration due to deflection of flow against the bank (Harmon et al., 1986) or growth and stabilization of bars and islands (Montgomery et al., 1995). Planform changes are generally limited to larger, relatively low-gradient streams which are not highly constrained by adjacent hillslopes.

LWD may also control the location and frequency of pools and riffles and reach-level morphology. Montgomery and Buffington (1997) argue that LWD can force a pool-riffle morphology in a channel that would otherwise have a plane-bed morphology lacking in pools or riffles. In a survey of several streams in southeast Alaska and Washington, Montgomery et al. (1995) found that pool spacing was inversely proportional to frequency of LWD pieces in pool-riffle, plane-bed, and

forced pool-riffle channels, but was unrelated to LWD frequency in steeper step-pool channels.

A commonly reported and readily observable effect of channel-spanning LWD accumulations is an increase in channel width due to bank erosion and/or sediment deposition within the channel (Keller and Swanson, 1979; Keller and Tally, 1979; Hogan, 1985). Less well documented is the effect of LWD on the variability of channel width. Zimmerman et al. (1967) found that the variation in channel width was greater in forested reaches than non-forested, sod-bank reaches in small watersheds (<6 km²) in the Sleepers River basin of New Hampshire, which they attributed to LWD in the channel and tree root mats on the bank, but the influence of LWD on variability of channel width in larger channels was minimal. Nakamura and Swanson (1993) reported that variance in width in Mack Creek, a 3rd order stream in the western Oregon Cascades, was least for bedrock-controlled sections, where LWD had little effect on channel morphology, and was greater for sections with large LWD capable of spanning the channel than for sections without appreciable LWD. Variance in width was greatest where channel spanning debris jams were present.

In headwater streams occupying narrow, steep-sided valleys, the morphologic influence of LWD is expressed by the creation of a stepped longitudinal channel profile rather than through effects on channel planform geometry (Keller and Swanson, 1979; Nakamura and Swanson, 1993; Montgomery et al, 1995). The values reported in the literature for the proportion of channel fall controlled by LWD vary widely, from an average of 6% for 1st to 5th order channels in the Oregon Coast Range (Marston, 1982) to as much as 100% for headwater streams of the Rocky Mountains of Colorado and the White Mountains of Arizona (Heede, 1972a, 1972b, 1977). The degree to which LWD controls the stream profile is largely determined by the size of the LWD relative to the channel and the ability of the channel to bypass obstructions (Harmon et al., 1986). Bilby (1981) found that the percentage of channel fall controlled by LWD decreased systematically with increasing stream order in the Hubbard Brook Experimental Forest in New Hampshire, from 52% for 1st order streams to 46% and 10% for 2nd and 3rd order streams, respectively. Marston (1982) found a more complex pattern in a survey of 163 km of 1st through 5th order streams in

the Oregon Coast Range, where the frequency of LWD-controlled steps in the channel profile reached a maximum of 4 per km for 3$^{rd}$ order channels but the total fall was greatest for 4$^{th}$ order channels due to larger average step size.

Another reported effect of LWD on the longitudinal profile of stream channels is to increase the variance in depth along the channel thalweg and in pools (Hogan, 1985; Lisle, 1995). Lisle (1995) found that variance of residual depth along the channel thalweg decreased significantly after total removal of LWD from low-sinuosity reaches in a low-gradient stream with high wood loading from the 1980 eruption of Mt. St. Helens, but variance in residual depth changed little in two higher sinuosity reaches from which LWD was removed. Longitudinal variance in channel depth has been shown to be strongly positively correlated to salmonid population in some streams (Bienz, 1998).

It might be anticipated that the creation of a stepped longitudinal profile by LWD, with its implied alternation of low-and high-gradient channel segments, would be accompanied by a corresponding variation in bed material particle size, with a fining of bed material upstream of steps and a coarsening downstream as has been reported by Chin (1989) for boulder steps. Although such a pattern is readily observable in the field, surprisingly few published reports have documented it. However, particle-size data showing a pattern of bed material enriched in fine particles upstream of channel-spanning LWD structures and relatively depauperate of fines downstream have recently been reported for low order streams in the Queen Charlotte Islands of British Columbia (Rice and Church, 1996) and in Vermont (Thompson, 1995).

## 2.2 Influence of LWD on Sediment Storage and Transport

LWD also profoundly influences sediment storage and transport. Several researchers have found that LWD structures comprise the dominant sediment storage sites in at least some steep forested mountain streams (Megahan and Nowlin, 1976; Thompson, 1995; Montgomery et al., 1996). Montgomery et al. (1996) found that LWD can cause alluvial channels to exist where bedrock channels would otherwise be

expected due to high bed shear stress and low sediment supply. Other workers have estimated that individual pieces or accumulations of LWD create storage sites for sediment accumulations amounting to as much as 10 to 15 times the annual sediment yield of some mountain streams (Megahan and Nowlin, 1976; Swanson and Lienkaemper, 1978; Megahan, 1982; Swanson and Fredriksen, 1982). Several studies have documented the influence of LWD on sediment storage within channels by measuring sediment yield or volume of sediment stored upstream of LWD accumulations before and after experimental removal of LWD from stream channels, or by comparing changes in sediment yield or storage in reaches in which LWD was experimentally removed with that from similar undisturbed reaches (Baker, 1979; Beschta, 1979; Bilby, 1981, 1984; Heede, 1985; Lisle, 1986, 1995; MacDonald and Keller, 1983, 1987).

LWD accumulations can facilitate in-channel sediment deposition and stabilize sediment deposits both upstream and downstream of the accumulation. Channel-spanning logs or debris jams commonly form leaky dams, creating large upstream pools which become relatively long-term sediment storage sites. Unlike either scour pools created downstream of flow obstructions or other sediment storage sites such as riffles and bars, backwater pools upstream of LWD are relatively low-energy (hence, depositional) environments even during high flows, making them more stable sediment storage sites (Thompson, 1995). Many channel-spanning LWD pieces or accumulations are stable for decades or longer (Swanson and Lienkaemper, 1978; Swanson et al., 1984; Hogan, 1987; Lienkaemper and Swanson, 1987). Based on the ages of nurse trees growing on them, the minimum age of LWD jams averaged 50 years in $3^{rd}$ to $4^{th}$-order streams in old-growth forest in Oregon sampled by Gregory (1991), with a maximum age of 150 years.

Smaller or marginal LWD which does not span the entire channel but which is still too large or well-anchored to be moved readily by the stream often anchors bedload deposits (i.e., bars) along the channel margins. In lower gradient streams (which also tend to be larger streams), LWD often anchors downstream as well as upstream sediment accumulations (Keller and Swanson, 1979); the latter typically take the form of marginal bars deposited in eddies downstream of the flow obstruction.

In addition to storing sediment, LWD can also reduce the bedload transport efficiency of a stream (Heede, 1972a, 1972b; Swanson and Lienkaemper, 1978; Beschta, 1979; Bilby, 1981; Megahan, 1982; Nakamura and Swanson, 1993). By dissipating flow energy (Heede, 1975; Marston, 1982) and creating depositional environments that are stable even at relatively high flows (Thompson, 1995), LWD accumulations reduce the likelihood that bed particles will be entrained during competent flows and reduce the mean travel distance of those particles that are entrained, thus reducing sediment transport efficiency.

## 2.3    Influence of LWD on Magnitude and Frequency of Channel Change

Previous research has shown that LWD can act to either to either a stabilize or destabilize stream channels. Bevan (1948-49) concluded that LWD was responsible for more channel changes than any other agent in the Middle Fork Willamette River in Oregon. Keller and Swanson (1979) argued that debris jams (channel-spanning accumulations of LWD) can locally either accelerate or retard channel bed and bank erosion or deposition and provided a number of examples. Nakamura and Swanson (1993) found that the largest changes in a 10-year record of cross section profiles in a 5th-order stream in the western Oregon Cascade Range were associated with scour and deposition around static old-growth Douglas-fir logs lying in the channel (typically stabilized by rootwads) and old-growth trees which fell into the channel from the stream bank during the period of study. The destabilizing effects of removing LWD from a channel have been well documented by experimental studies (Beschta, 1979; Bilby, 1981, 1984; Heede, 1985; Lisle, 1986; MacDonald and Keller, 1987; Smith et al., 1993a, 1993b; Lisle, 1995), but these studies have typically been short-term in nature and have not addressed the long-term effects of LWD removal on channel stability—i.e., is a channel without LWD, once it has adjusted to that condition, inherently more or less stable than it would be with LWD?

In his review of research on the environmental hydraulics of LWD in streams, Gippel (1995) emphasizes that large pieces of LWD, particularly channel-spanning LWD accumulations, act as large roughness elements that reduce reach-average flow

velocity. Such an effect has been documented by MacDonald and Keller (1987), who reported a 250% increase in local flow velocity after removal of a debris jam in Larry Damm Creek (northern California), and by Shields and Smith (1992), who found that reach average flow velocity at low flow in cleared sections of the Obion River (Tennessee) to be approximately 50% greater than in reaches that had not been cleared. Since average boundary shear stress is proportional to the square of mean flow velocity, a small reduction in the latter could translate into a significant reduction in the ability of the stream to erode its bed and banks. However, the effect of LWD on channel roughness and mean flow velocity has been shown by a number of workers to diminish or disappear entirely with increasing discharge in at least some streams (Lisle, 1986; Hecht and Woyshner, 1987; Shields and Smith, 1992). Thus, the channel-stabilizing influence of LWD through its effect on channel roughness and local mean flow velocity may be least significant during large flow events when channel change is most likely to occur, at least in streams where LWD structures are completely submerged during large floods.

If LWD stabilizes the channel, it must by definition reduce the frequency and/or magnitude of channel change. If, on the other hand, LWD de-stabilizes the channel, it should be associated with increased frequency and/or magnitude of channel change. The diverse and sometimes contradictory claims in the literature about the roles of LWD as either a stabilizing or a de-stabilizing influence on channel morphology result in part from the importance of the specific arrangement and structure of LWD in determining its local impact on channel form and process (i.e., all LWD is not functionally equal) and in part from the scale-dependence of the effects of LWD (e.g., the declining effect of LWD on channel roughness and mean flow velocity with increasing discharge). Several authors explicitly address the issue of the spatial scale dependence of LWD function in stream channels (e.g., Keller and Swanson, 1979; Marston, 1982; Nakamura and Swanson, 1993; Gippel, 1995). These studies suggest that the role of LWD changes from that of a static structural channel element with a spatial distribution controlled by input processes in low-order headwater streams to an increasingly dynamic and fluvially controlled element as stream order increases. However, few, if any, studies have directly addressed the question of

whether LWD affects channel stability in terms of changing the temporal frequency or pattern of channel change.

Adenlof and Wohl (1994, p. 83) argue that "woody debris both traps sediment and increases form roughness, thus contributing to channel stability." Similarly, in his study of the effects of experimental woody debris removal on a channel impacted by the 1980 eruption of Mt. St. Helens, Washington, Lisle (1995, p. 1808) concluded that "during large-scale, severe disturbances, LWD can diversify hydraulic forces and maintain structural integrity, thereby counteracting the tendency for large sediment inputs to inundate and simplify aquatic ecosystems." Gippel (1995) also emphasizes the role of LWD in providing a varied flow environment and reducing mean flow velocity. By increasing the spatial variability in local hydraulic conditions within the channel, LWD may increase the local variability of channel response to major floods. But at the reach scale, the ability of LWD to reduce mean flow velocity should act to stabilize the channel bed and banks during peak discharges, at least in channels where LWD elements are large relative to the bankfull channel cross section.

# 3   Study Site and Methods

## 3.1   Study Site

The Mack Creek study site lies at an elevation of approximately 750 m within the H.J. Andrews Experimental Forest (Andrews Forest) (Figure 3.1). Mack Creek is a 3rd-order watershed with a drainage area of approximately 5.8 km$^2$ at the gaging station located about 1 km upstream of the junction with Lookout Creek. Since the late 1970s, the lower portion of Mack Creek has been the site of intensive, long-term studies focusing on riparian forest dynamics and the fate and functions of LWD in fluvial systems (e.g., Swanson et al., 1976; Swanson and Lienkaemper, 1978; Swanson et al., 1982a, 1982b; Lienkaemper and Swanson, 1987; Nakamura and Swanson, 1993, 1994).

This study capitalizes on some of that long-term monitoring data, including two sets of permanent reference channel cross sections in nearly adjacent, contrasting reaches. The upper reach (old-growth site) lies just upstream of the gaging station and a road crossing (Figure 3.2); this reach contains 12 cross sections established in 1978 within an old-growth forest dominated by Douglas-fir with lesser amounts of western hemlock and western redcedar. The lower reach (clearcut site) has 20 cross sections established in 1981 and lies immediately downstream of the gaging station; the hillslopes adjacent to the reach were clearcut in 1964-65, and most of the large woody debris remaining in the channel was flushed downstream by a major flood in December 1964. The distribution of LWD (all pieces >10 cm diameter and >1 m in length) has been monitored over an approximately 1-km stream reach encompassing the two cross section sites since the mid 1980s. The two reaches have approximately the same channel gradient (10.0% for the old-growth reach vs. 9.6% for the clearcut reach) and experience essentially the same discharge; they differ chiefly in the following respects:

1.  LWD is abundant in the old-growth reach and largely absent in the clearcut reach (Figure 3.2), and
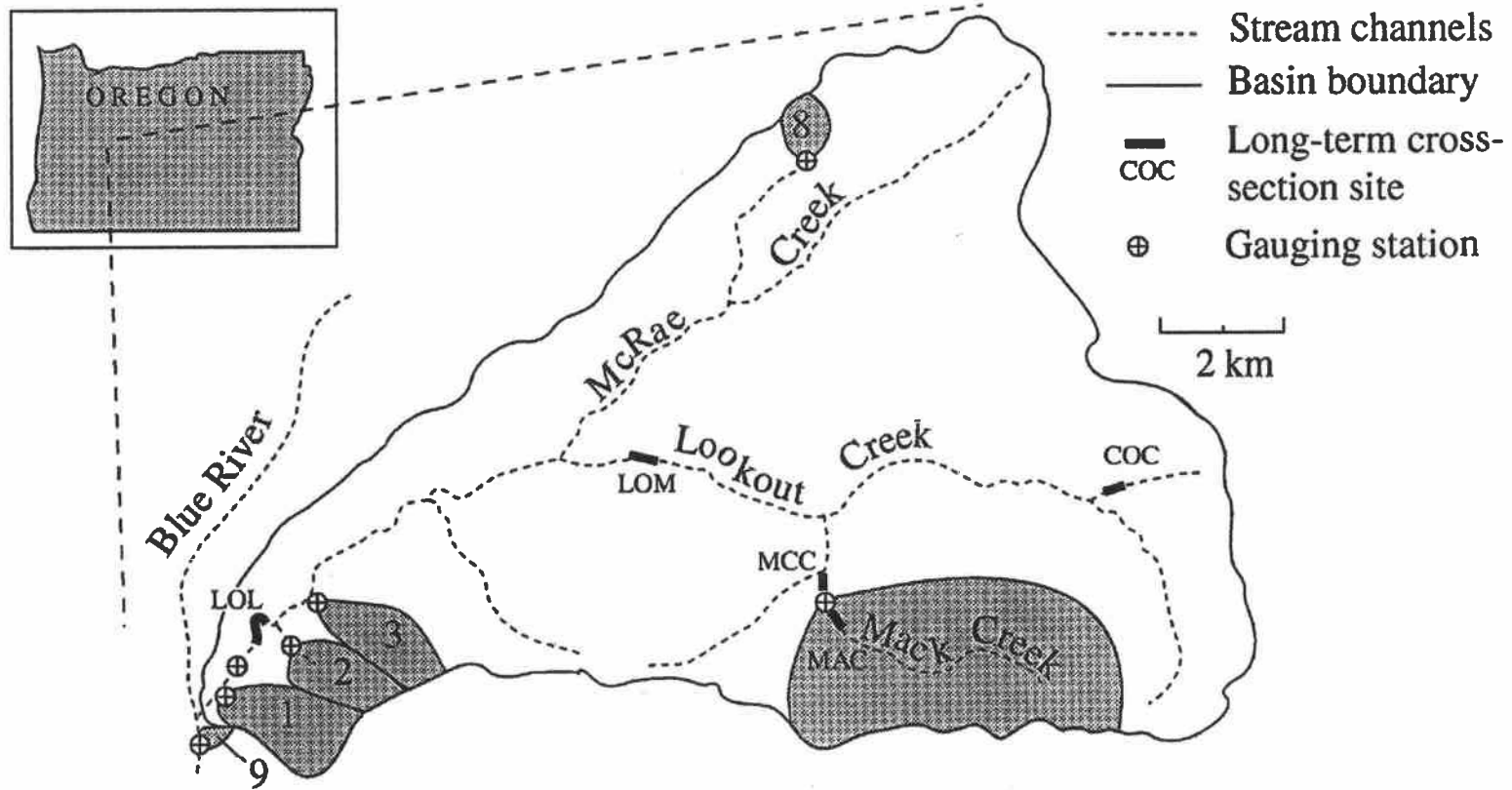
Figure 3.1. Location of long-term cross section monitoring sites, small experimental watersheds, and gaging stations in the Lookout Creek watershed (H.J. Andrews Experimental Forest).

Figure 3.2. Map of Mack Creek old-growth and clearcut cross section sites showing LWD structures, cross section locations, and longitudinal distribution of LWD. Bars at top of lower plot show the number of pieces of LWD >10 m in length located at least partially within the channel, counted in 10-m channel segments. Bottom portion of lower plot shows the estimated volume LWD in 10-m channel segments within each of four zones relative to the channel: *zone 1*– within the low-flow channel; *zone 2*– within the bankfull active channel outside or suspended above the low-flow channel; *zone 3*– suspended above bankfull stage within the bankfull channel width; and *zone 4*– laterally outside the bankfull channel. LWD data from S. V. Gregory (unpublished data).
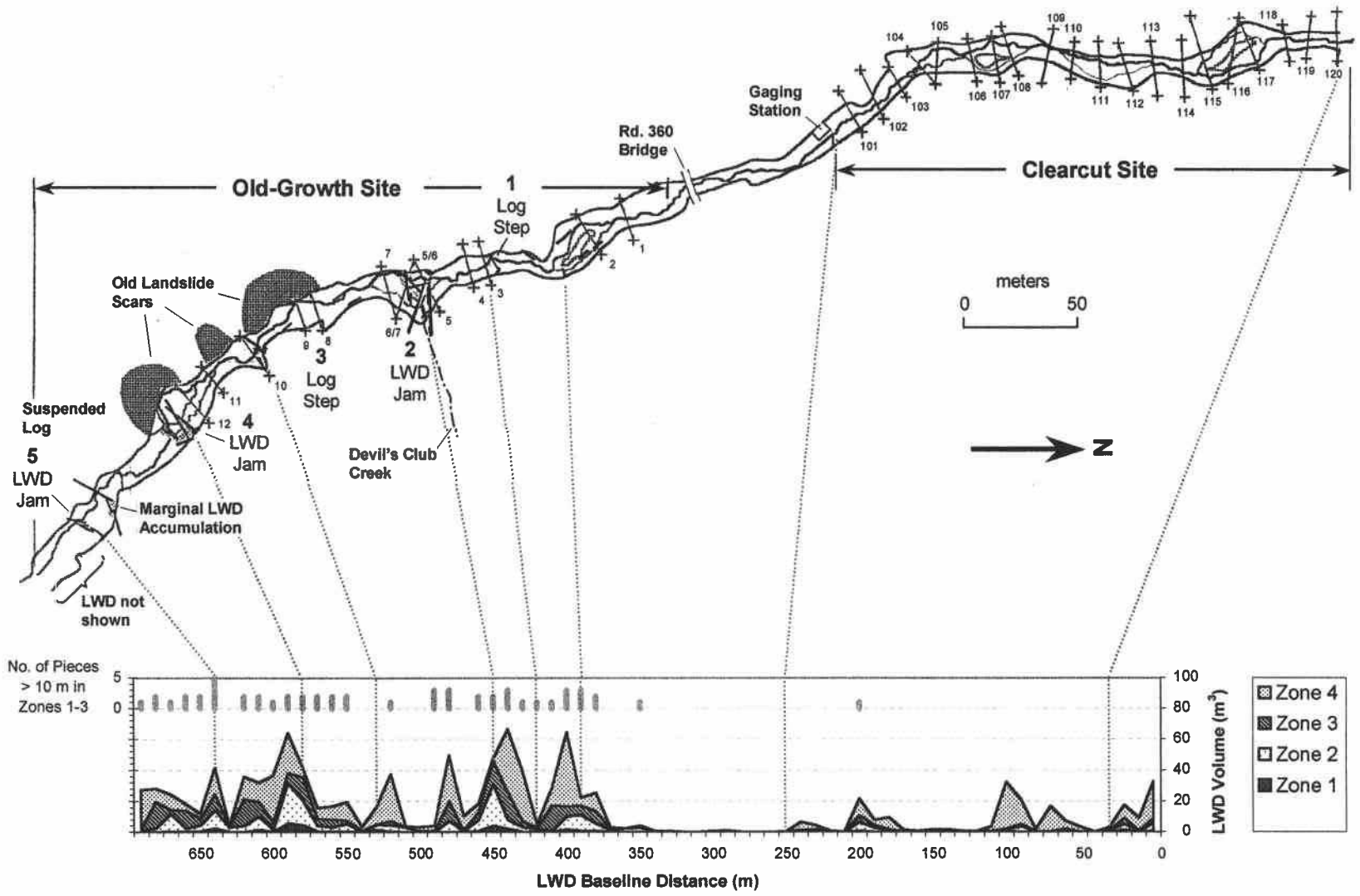
Figure 3.2.

2. the old-growth reach is confined by steep hillslopes in a narrow valley, while the valley floor is wider and the hillslopes generally are not immediately adjacent to the channel in the clearcut reach.

The contrast between the old-growth and clearcut sites is shown clearly in the lower plot of Figure 3.2, based on data provided by S. V. Gregory (unpublished data). The estimated volume of LWD within the channel (zones 1-3; see Section 2.1) averages 0.16 $m^3$/m (range: 0.00 to 1.08) within the clearcut reach (40-260 m on the LWD baseline [Figure 3.2]) and 1.23 $m^3$/m (range: 0.05 to 4.6) in the old-growth reach (340-680 m on the LWD baseline). Thus, there is approximately 7.6 times as much in-channel LWD in the old-growth reach as in the clearcut reach. Even more striking is the difference in large LWD pieces capable of forming significant structural elements in the channel. Only a single LWD piece >10 m in length was present within the channel in the clearcut reach in 1996, compared with 51 pieces in the old-growth reach (Figure 3.2); these values are equivalent to frequencies of 0.45 and 15 pieces per 100 m, respectively.

Following Keller and Swanson (1979), LWD is here defined as logs, limbs, and other woody debris that are greater than 10 cm in mean diameter. Fine woody debris or organic debris (OD) refers to woody debris less than 10 cm in diameter. A LWD accumulation is any accumulation of 3 or more LWD pieces and associated OD. Two types of channel-spanning LWD structures are recognized here. A LWD jam is a channel-spanning accumulation consisting of 3 or more key pieces and associated smaller LWD and OD, and sediment which is more than one log diameter in height and which typically anchors a significant upstream sediment accumulation. A log step is a structure roughly one log diameter in height, typically consisting of a single key piece (although it may involve 2 or more pieces that are not vertically stacked and that collectively span the channel) partially or completely buried on the upstream face by accumulated sediment.

Within the old-growth reach, major peaks in LWD abundance generally—but not invariably—correspond to significant LWD structures that affect channel morphology (Figure 3.2). It is important to keep in mind that LWD outside the channel (i.e., in zone 4) cannot directly influence channel morphology, and that LWD

within zone 3 (suspended above the bankfull channel) may or may not interact with the channel depending upon how far above the channel it lies and whether it rests on other LWD within the channel. Thus, the large LWD peak at 405 m, which consists principally of LWD in zone 4, is not particularly significant in terms of its potential effect on channel morphology. However, this peak does correspond to an open-framework channel-spanning LWD accumulation that was partly dismantled by the February 1996 flood. Existing channel-spanning LWD jams show up as peaks in LWD volume at 455, 590, and 645 m (Figure 3.2); smaller LWD peaks at 485, 625 and 685 m do not correspond to geomorphically significant structures. On the other hand, single-log steps—which, as will be shown, are significant as channel structures and sediment accumulations sites—do not show up as peaks on the longitudinal plot of LWD density.

## 3.2    Historical Data Sets

Twelve established reference cross sections in the old-growth site and 20 in the clearcut site (Figure 3.2) have been surveyed on a near-annual basis beginning in 1978 and 1981, respectively. Cross section profiles were surveyed using a builders' auto-level and a telescoping fiberglass stadia rod graduated in 0.5-cm increments. The position of the stadia rod (distance from a permanent reference point on the left bank, viewed in the upstream direction) was measured to the nearest 0.1 m using a fiberglass measuring tape stretched between the permanent cross section end posts. The height of the instrument line-of-sight above the base of the rod was recorded to the nearest 0.01 m. Measurements were taken at 0.5-m intervals along the tape and at slope break points. The substrate at each rod position was also recorded as a 2-letter code. The chief substrate categories (within the active channel) were boulder (>25 cm diameter), cobble (5 to 25 cm), gravel (2 mm to 5 cm), fine sediment (<2 mm; typically sand), log, suspended log, and organic debris (woody debris <10 cm in diameter). Black-and-white photographs of each cross section, typically one upstream and one downstream view, were routinely taken during cross section surveys beginning in 1995.

To assess bed material surface particle size and its variability, modified Wolman (1954) pebble counts were performed at each cross section location beginning with the 1995 survey (Appendix A). Pebble counts consisted of measuring the b-axis diameter of 100 particles selected at random from the streambed within the active channel and within one meter of the cross section line. Particles were selected by traversing the channel along the cross section line and reaching down with one finger while looking away from the streambed to avoid biasing selection. Each particle was measured to the nearest 5 mm (or the nearest 1 mm for particles less than about 5 cm in diameter) using a steel tape measure. Particles less than 2 mm in diameter (i.e., sand) were recorded simply as <2 mm. For large partially buried particles the length of the apparent intermediate axis of the exposed portion of the particle was measured.

Tagging and tracking of LWD movement in Mack Creek was initiated in 1986 by S. V. Gregory and colleagues (Ashkenas, personal communication). A longitudinal baseline extending approximately 1 km upstream from the downstream end of the clearcut (about 40 m downstream of XS 120, Figure 3.2) was established with permanent reference markers on both streambanks at approximate 20-m intervals. Each piece of woody debris greater than 10 cm in diameter and 1 m in length was labeled in the middle and both ends using metal or plastic tags bearing a unique ID number. The longitudinal position of each piece is tracked by assigning the piece to a 10-m channel section corresponding to the upstream or downstream half one of the 20-m baseline segments between permanent reference markers. In addition to LWD lying in or overhanging the channel, pieces lying on the bank or floodplain are included if they are judged to be close enough to the channel to interact with extreme floods. The LWD inventory is updated each year, and data on piece size, location, and condition are recorded for each newly tagged piece and all pieces determined to have moved since the previous year.

## 3.3    Additional Data Acquisition

Additional field data were collected during the summer of 1997 to more completely characterize channel morphology within the study reaches. Field work included surveying the positions of the cross section endpoint stakes, surveying a high-resolution longitudinal profile of the channel thalweg, mapping the margins of the active channel floodway, and counting the frequency of large boulders (>1-m diameter) within the active channel floodway. The locations of large logs and woody debris accumulations was also mapped within the old-growth reach.

### 3.3.1    CROSS SECTION ENDPOINT SURVEY

Although the cross sections have been re-surveyed regularly since they were first established in the 1978 (old-growth site) and 1981 (clearcut site), the locations of the cross section end posts had not been previously mapped or surveyed. Therefore, in order to establish the spatial relationship of the cross sections to one another, the reference post locations were surveyed during the summer of 1997 (Figure 3.2). First, the relative elevations of the cross section reference posts (measured at the ground surface) were surveyed using a builders' auto-level. Subsequently, both the map position and relative elevation of each end post were surveyed using a laser theodolite consisting of a tripod-mounted laser range-finder with a built-in electronically read clinometer in a housing to which a manual sight-through compass could be mounted. Effective precision of the instrument was approximately 0.2% on the horizontal distance (or about +/- 5 cm in 25 m); vertical precision was within approximately 2 to 3 cm over 25 m horizontal distance. The mounted manual compass was graduated in 0.5-degree increments, and readings were interpolated to the nearest 0.1 degree; readings were typically reproducible to within 0.2 degree, which is equivalent to 9 cm at a distance of 25 m.

### 3.3.2 LONGITUDINAL PROFILE SURVEY

Because high-gradient streams tend to dissipate energy through vertical flow oscillations (e.g., step-pool structures; Grant et al., 1990) rather than the lateral oscillations characteristic of low-gradient streams (e.g., meanders and pool-riffle structures), cross sections at best offer an incomplete characterization of channel morphology in a steep mountain stream such as Mack Creek. Therefore, a high-resolution longitudinal profile was surveyed along the channel thalweg of approximately 1 km of Mack Creek, including both the old-growth and clearcut sites.

The survey was performed using the laser theodolite described above. Points were selected along the main thalweg at intervals of approximately one meter, or a smaller interval where necessary to characterize abrupt changes in channel slope or elevation—e.g., at the crest and base of abrupt steps in the longitudinal profile. This resulted in an average distance of 0.9 m between surveyed points along the longitudinal profile. At points where the flow divided around a mid-channel bar, the profile followed the larger channel (or in some cases both channels). The location of any steps greater than about 30 cm in height was noted in the comment column of the field notes. When traversing pools, it was attempted to include the upstream and downstream endpoints of the pool as well as the deepest point located along the thalweg.

Concurrently with the longitudinal profile survey, the margins of the active channel floodway were surveyed at intervals of approximately 5 to 10 m. The objective of this effort was to generate a map of the channel margin. Channel margin survey points were selected using the following criteria: reasonably well-defined channel boundary, clear line of sight from the instrument, inflection points (to capture bends or changes in channel width), and distance from the last surveyed point.

The longitudinal profile and channel margin survey of the 700-m reach containing the old-growth and clearcut sites was completed between July 23 and August 7, 1997. Subsequently, the longitudinal profile survey was extended an additional 100 m upstream of the uppermost cross section on September 5, 1997 to include more LWD structures in the old-growth portion of the stream channel. The

sample point spacing for this upstream extension of the longitudinal profile averaged 1.0 m.

Survey data were entered into a spreadsheet, where the measured compass bearings and horizontal and vertical distances were used to calculate the coordinates (x,y,z) of each point with respect to an arbitrary reference point. The coordinate grid was aligned so that north is oriented in the +y direction and east in the +x direction.

### 3.3.3 BOULDER FREQUENCY

Longitudinal variations in the frequency of large boulders in a channel may be an indicator of spatial variations in fluvial and hillslope processes which shape channel and valley floor morphology (Grant and Swanson, 1995; Lambert, 1997) and may be important in the stabilization of LWD jams (Likens and Bilby, 1982). The number of boulders with an intermediate (b-axis) diameter ≥ 1 m within each 20-m channel segment along the LWD baseline was counted for the old-growth and clear-reaches shown in Figure 3.2. In addition to exposed boulders lying in the channel, partially buried boulders were counted if it could be determined with reasonable certainty that they met the size criterion. Boulders embedded in the bank were also counted if they would interact with a bankfull discharge or if they were undercut by the channel.

### 3.4 Data Analysis

Cross section surveys from 1995 and 1996 (Appendix B) were used to estimate the magnitude of channel scour and fill at each cross section location in response to the flood of February 1996. First, data points corresponding to logs lying on or suspended above the channel bed were filtered out, so that the cross section profiles would represent the configuration of the channel boundary exclusive of LWD. Then a public-domain software package, WinXSPRO (Grant et al., 1986; USDA Forest Service, 1998), was used to calculate the area between cross section profiles from consecutive survey dates to determine the cross sectional area of channel scour and fill

(Figure 3.3). These quantities may be thought of as the net volume per unit channel length of bed material eroded from or deposited within the channel, respectively. From this perspective, each cross section represents a single sample point for channel response in a longitudinal transect of the stream channel.
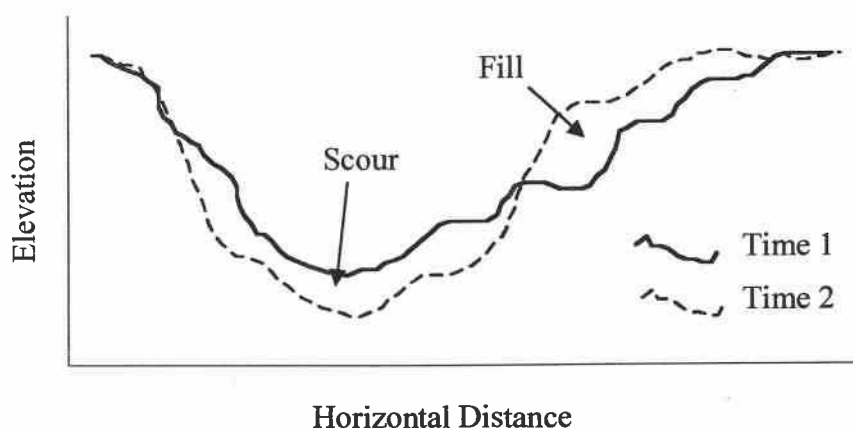


Figure 3.3. Determining cross-sectional area of channel scour and fill using consecutive cross section profile surveys.

The estimates of scour and deposition at each cross section location can be combined to form two other measures of channel response. The *net cross section change* is the algebraic sum of scour (a negative value) and fill (a positive value). A negative value for the net cross section change represents a net loss of bed and/or bank material, or net scour, while a positive value represents a net gain of bed/bank material, or net deposition. The *total cross section change* is the sum of the absolute values of scour and fill, and is a measure of the absolute magnitude of channel response (volume of sediment reworked per unit channel length) at a single cross section. To obtain a measure of channel response at the *reach* scale, the estimates of scour, deposition, net change and total change for all cross sections at a site (i.e., old-growth or clearcut) were averaged to yield a reach-average response.

Bed material particle size data collected in conjunction with cross section surveys during the years 1995-1997 were used for the following purposes:

1. to look for reach-scale differences in the bed surface particle size distribution between the old-growth and clearcut sites,

2. to assess whether the within-reach spatial variability in bed surface particle size differs between the two reaches,

3. to assess whether LWD structures significantly influence bed surface particle size locally within the old-growth reach (e.g., is bed material finer immediately upstream of LWD structures?), and

4. to determine whether the bed surface particle size distribution at the two sites changed in response to the February 1996 flood.

Particle size data were analyzed in two ways. First, the particle size distribution for each sample (one sample at each cross section location) was represented by summary statistics or "representative" particle sizes, in particular the $D_{50}$ (median particle diameter) and the $D_{84}$ (diameter of a particle larger than 84% of the particles in the sample) (Appendix A). Where sample sizes were sufficient (e.g., reach-scale comparisons between sites or between years at either site), differences were tested for significance using a Student's t-test after log-transforming the data (to reduce skew in particle size distribution). A second way the particle size data were analyzed was to combine all the samples from each population being sampled (e.g., old-growth site vs. clearcut site) and compute a cumulative particle size frequency distribution based on the composite samples. The resultant empirical cumulative density functions, or CDFs, were then compared graphically.

# 4   Results

## 4.1   Channel Morphology

### 4.1.1   CHANNEL WIDTH AND PLANFORM PATTERN

Measurements of channel width in the old-growth and clearcut reaches at Mack Creek are consistent with previously reported findings that reaches having abundant LWD have greater average channel width and variation in channel width than reaches with little LWD (e.g., Zimmerman et al., 1967; Keller and Swanson, 1979; Nakamura and Swanson, 1993).  Mean channel width is greater for the old-growth site (13.0 m, n = 17) than for the clearcut site (10.7 m, n = 11), a difference which is marginally statistically significant (1-sided p-value = 0.044; t-test).  This difference in width is all the more significant given that the valley floor widens downstream of the road crossing (Figure 3.2); thus, the channel is wider within the old-growth reach even though it is noticeably more constrained by the valley walls.

The old-growth reach is also slightly more variable in width than the clearcut reach, as reflected in its higher coefficient of variation for channel width (3.80 for the old-growth reach vs. 3.25 for the clearcut reach).  Variations in channel width are clearly associated with LWD structures (Figure 3.2).  Channel width at four of five channel-spanning log steps or LWD jams is greater than the reach average of 13.0 m; the mean width at all 5 locations is 16.7 m, or 28% greater than the reach average (Table 4.1).  Channel widths at the two log step locations are close to the reach average (9.5 and 15 m), while widths at the three LWD jam locations average 19.7 m, or 52% greater than the reach average.

Another difference between the old-growth and clearcut reaches, which is apparent in the plan view channel map (Figure 3.2), is that the latter tends to bifurcate frequently, with mid-channel bars separating the main or low-flow channel from a secondary channel which is active only during somewhat higher (wet season) flows.  Within the old-growth reach, only a short (~30 m) length of channel near XS 2 has a divided channel.  (Flow sometimes splits around gravel deposits on the upstream side

Table 4.1. Channel width variations at Mack Creek old-growth site associated with LWD.

| | Channel-spanning LWD | LWD Jams | Log Steps | Entire Reach |
|---|---|---|---|---|
| *Widths (m)* | 16.5, 20.5, 15, 22, 9.5 | 16, 20.5, 22 | 15, 9.5 | --- |
| *Avg. width (m)* | 16.7 | 19.7 | 12.3 | 13.0 |
| *% difference from reach avg.* | +28% | +52% | -5% | --- |

of LWD jams, and downstream of the lower two LWD jams the channel widens while the thalweg becomes poorly defined, but distinct multiple channels generally do not occur within the old-growth reach.) This difference may be due to differences in riparian vegetation: dense willow thickets stabilize mid-channel bars in the clearcut reach but are absent from the old-growth reach.

### 4.1.2 LONGITUDINAL PROFILE

The longitudinal profile reveals significant differences in the structure of the channel between the old-growth and clearcut reaches (Figure 4.1). Significant inflections in the longitudinal profile are associated with each of the five channel-spanning LWD structures labeled in Figure 3.2. Overall, approximately 30% of the total elevation loss in the longitudinal profile within the old-growth reach is associated with these LWD structures. None of the elevation loss in the profile is associated with LWD within the clearcut reach.

LWD-caused steps in the longitudinal profile of the old-growth reach are significantly larger than most boulder-related steps in either reach. A few large boulder steps in the clearcut reach (e.g., at XS 106 and 107, Figure 4.1) have a height of 1 m or more, rivaling the log steps (LWD structures 1 and 3, Figure 4.1), but the boulder steps do not create the 20- to 40-m long segments of low-gradient channel that are found upstream of the LWD structures. The two log steps have heights of about 1

Figure 4.1. Longitudinal profile for the portion of Mack Creek shown in Figure 3.2. The longitudinal distance is based on an 11-point moving average of the $x$- and $y$-coordinates of the surveyed points along the channel thalweg, but the vertical coordinate has not been smoothed. The upper row of labels for the horizontal (longitudinal distance) axis apply to the upper plot (old-growth reach), while the lower row of labels apply to the lower plot (clearcut reach). Numbered features correspond to numbered LWD structures in Figure 3.2.
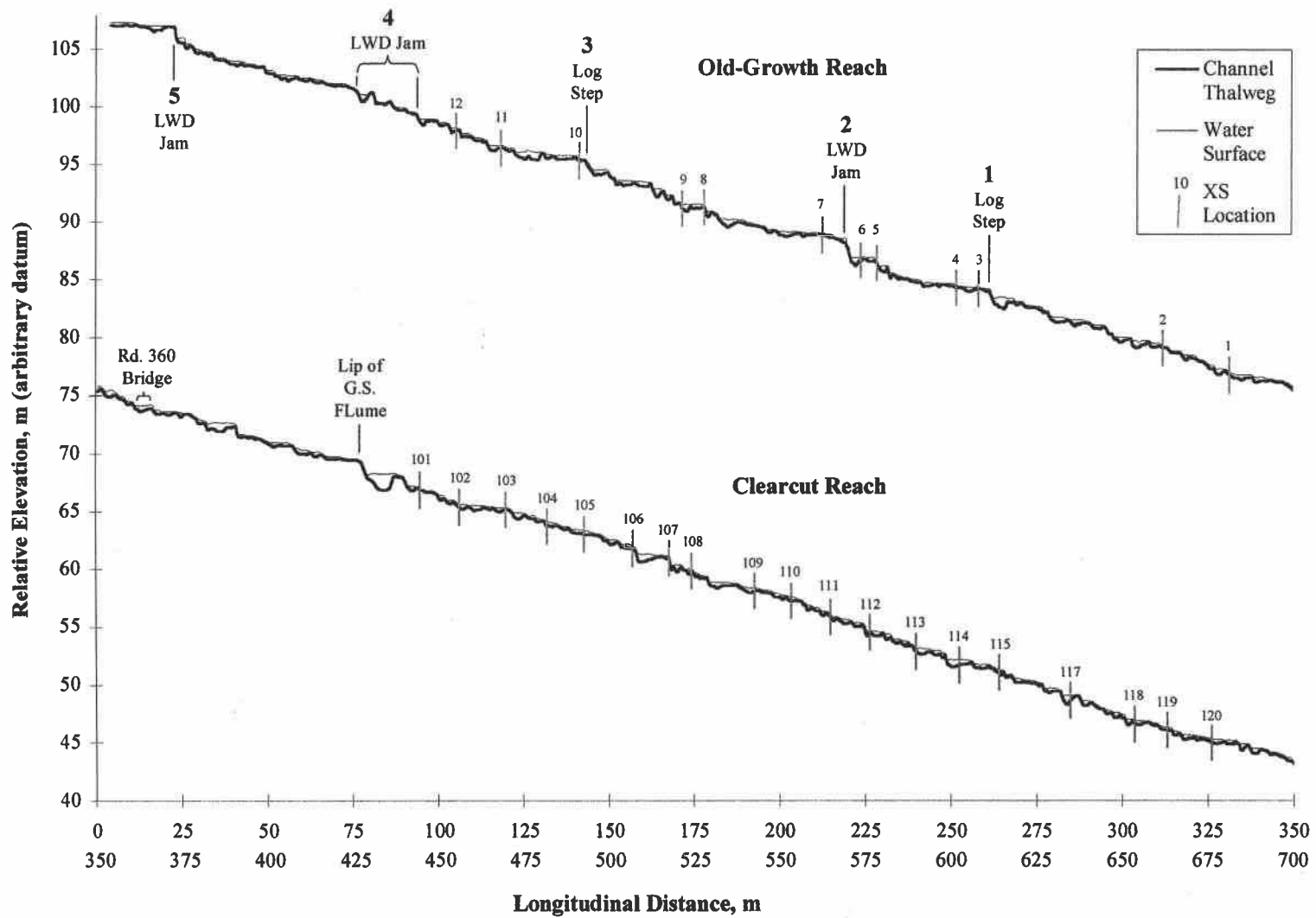
Figure 4.1. (continued)

to 1.5 m each (Figure 4.2), while the LWD jams produce steps about 2 to 2.5 m in height (Figure 4.3).



Figure 4.2. Log step at the Mack Creek old-growth (MAC) site. Cross section 10 crosses the channel just upstream of the step. Note the fine gravel deposit upstream of the step. Orange disc is 30 cm (1 ft) in diameter; step height is just over 1 m.

The middle LWD jam (LWD structure 4) does not show up as a step in the longitudinal profile (Figure 4.1) because the thalweg (and most of the flow, even at high discharge) cuts diagonally through the jam and around the end of one of the key logs (Figure 3.2), descending over a series of boulder steps within the jam and lengthening the distance over which the drop occurs (Figure 4.4). The jam does correspond a convex inflection point in the longitudinal profile, however, with at least 25 to 30 m of low-gradient channel upstream.

The differences in the structure of the longitudinal profile between the old-growth and clearcut reaches are revealed more clearly in the smoothed, de-trended longitudinal profile (lower plots in Figures 4.5 [a] and [b]). A positive slope on the

Figure 4.3. View of channel at Mack Creek old-growth (MAC) site showing armored channel bed downstream of a large LWD jam. Vertical distance between water surface immediately up- and downstream of the jam is approximately 1.5 m; total height of the structure is a little over 2 m.

residual plots (i.e., where the residual increases in the downstream direction) indicates a section of channel with below-average slope, while a negative slope indicates a channel section with above-average slope. Peaks in the residual plot correspond to inflection points between channel segments with below-reach-average and above-reach-average slope. Major peaks in longitudinal profile residual plot for the old-growth reach correspond to significant LWD structures (Figure 4.5[a]), while peaks in the clearcut reach, where LWD structures are absent, are smaller and less well-defined (Figure 4.5[b]).

As suggested above, an important effect of large LWD on the channel is that it alters the frequency distribution of channel gradient along the longitudinal profile. Figures 4.6 (a) and (b) show the frequency distribution for the low-flow water surface gradient for the old-growth and clearcut reaches, respectively, calculated over a 10-m

Figure 4.4. View of channel within LWD jam (structure no. 4 in Figure 3.2). Flow is diverted down a boulder cascade and against the left bank, which consists of exposed bedrock. Note the gravel in the foreground, which is typical of sediment stored upstream of LWD jams in Mack Creek, but is relatively uncommon elsewhere in the channel.

interval centered on each point in a 5-point moving average of the longitudinal profile in Figure 4.1. The histograms reveal that the frequency distribution for local channel slope at the old-growth site is skewed toward low slopes, while local channel slope at the clearcut site is essentially normally distributed. The cumulative distribution curve for the local channel slope at the old-growth site (Figure 4.6[a]) has a flatter slope than the curve for the clearcut site (Figure 4.6[b]). This implies that the old-growth site has a more uniform distribution of local channel slopes, with less of the channel having slope close to the average value of 9.3% and more of the channel having significantly greater or lesser slope. Based on a 10-m moving average of the longitudinal profile (Figure 4.1), 36.9% of the channel in the old-growth reach had a local slope of $\leq 7\%$, vs. 20.4% of the channel within the clearcut reach, while 23.3% of the old-growth channel vs. 7.5% of the clearcut channel had a slope of $\leq 5\%$. Thus, the proportion of

Figure 4.5. Longitudinal plot showing quantity of LWD and channel characteristics at Mack Creek: (a) old-growth site; (b) clearcut site. For each site, the top plot shows the estimated volume of LWD within or suspended above the channel within each 10-m channel segment; the second pair of plots show a count of boulders with b-axis diameter >1 m within 20-m channel segments and the channel width at the midpoint of each segment; and the bottom plot shows the residual from a linear regression of bed (thalweg) elevation vs. distance. The bed elevation residual plot has been smoothed by applying a 9-point moving average to filter out high frequency oscillations.

**(a) Old-Growth (MAC) Site**
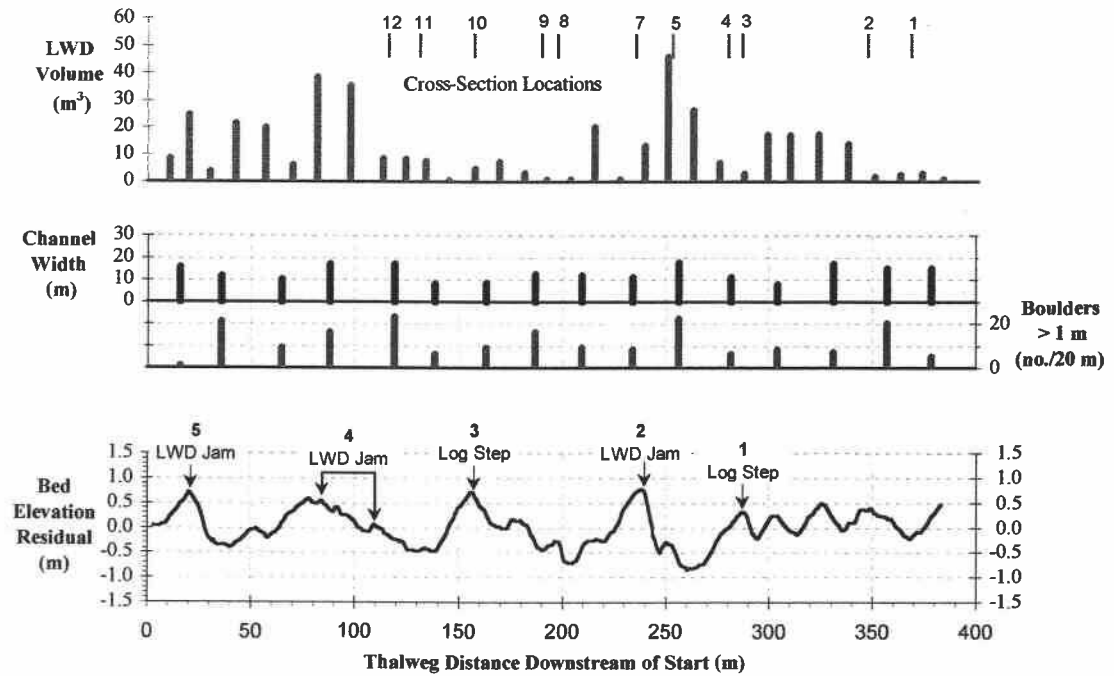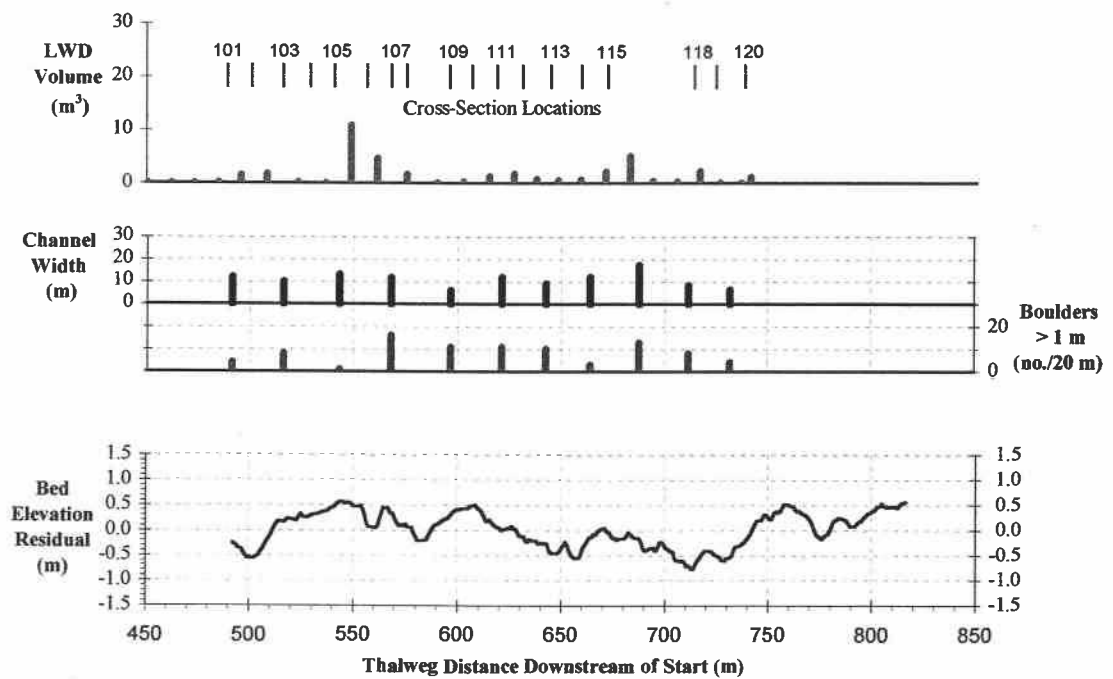


**(b) Clearcut (MCC) Site**



Figure 4.5 (continued)

(a)  Old Growth (MAC) Site
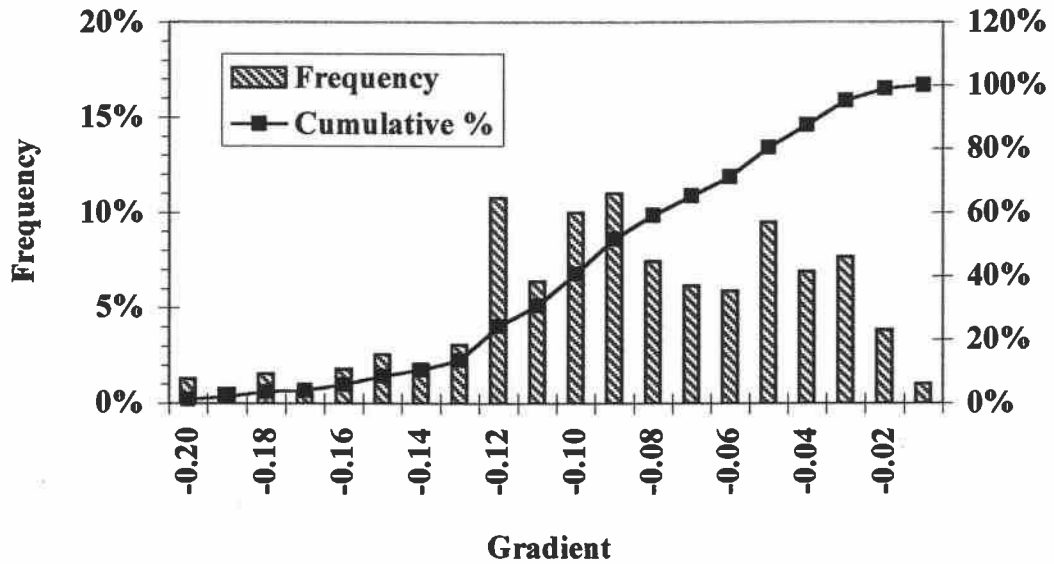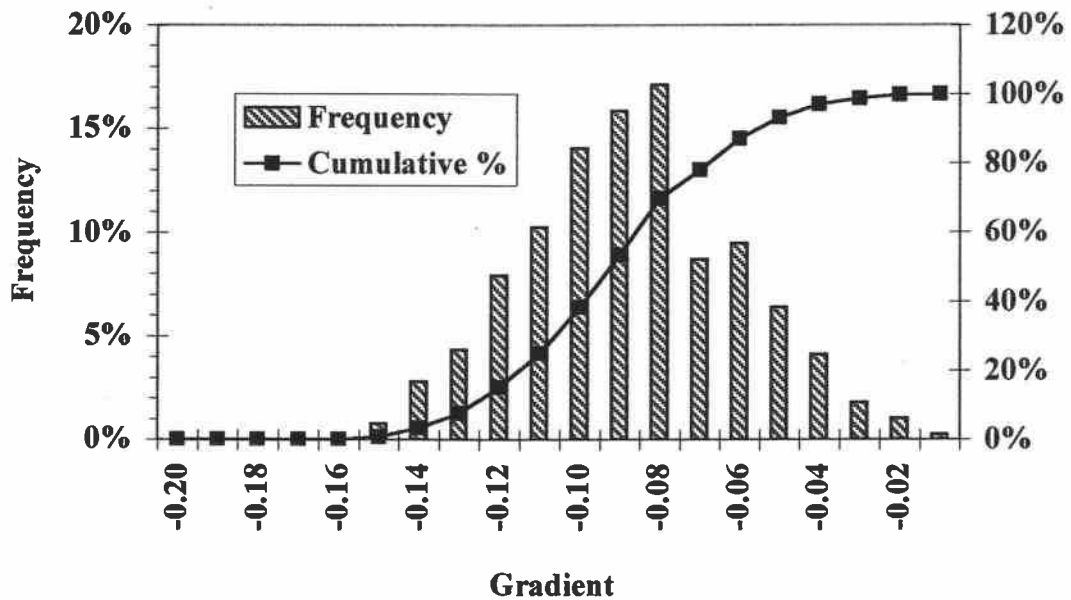


(b)  Clearcut (MCC) Site



Figure 4.6.  Frequency distribution for the local low-flow water surface gradient in Mack Creek:  (a) old-growth (MAC) site; (b) clearcut (MCC) site.  Water surface slope was calculated over a 10-m  interval centered on each point in a      5-point moving average of the longitudinal profile in Figure 4.1.

the channel in the old-growth reach with a bed slope of 5% or less was three times as great as in the clearcut reach.

There is a rather striking spatial correlation between the frequency of large boulders (>1 m b-axis diameter) and the LWD jams (Figure 4.5). Three of the four 20-m LWD baseline channel segments with boulder counts of 20 or more (i.e., ≥1 boulder per meter of channel length) are located immediately downstream of LWD jams (structures 2, 4 and 5; Figure 4.5[b]); the fourth is located just downstream of a former LWD accumulation just upstream of XS 2 that was partially dismantled by the February 1996 flood. Channel widths are also greater where the boulder counts are highest, suggesting that the greater boulder frequency may, in part, simply reflect greater streambed surface area. But other evidence suggests that increased channel width alone does not explain the pattern of variation in boulder frequency. For example, large boulders were much less abundant upstream than downstream of the uppermost LWD jam (structure 5 in Figure 4.5[a]), even though channel width was slightly greater upstream than downstream of the jam. Also, while conducting the boulder count, it was observed that exposed boulders meeting the size criterion were clearly clustered at the base of LWD structures and immediately downstream.

## 4.2 Channel Response to Flood of February 1996

### 4.2.1 CROSS SECTION RESPONSE

Cross section and particle size data for 1995-1997 reveal different responses to the February 1996 flood in the old-growth and clearcut reaches. In general, the dominant channel responses revealed by the cross sections and particle count data in the clearcut reach were scour and an associated increase in bed surface particle size, while the most pronounced changes in the old-growth reach were associated with aggradation upstream of LWD.

Of the 18 cross sections in the clearcut reach for which magnitude of change could be determined, 8 exhibited substantial scour (XS 101, 102, 107, 108, and 115) or moderate scour (XS 111, 112, and 114) as a result of the February 1996 flood (Table

Table 4.2. Summary of channel responses to the flood of February 1996 at the Mack Creek cross section locations.

| Cross-Section No. | Cross-Section Response [1] | | Textural Response |
|---|---|---|---|
| | total response | net response | |
| *Old-Growth Site* | | | |
| 1 | mod. scour | minor scour | coarsened |
| 2 | major scour | mod. scour | coarsened |
| 3 | major fill | major fill | fined |
| 4 | minor scour | no significant change | no change |
| 5 | minor scour | minor scour | fined |
| 6 | unclear | unclear | coarsened |
| 7 | major fill + minor scour | major fill | improved sorting |
| 8 | no significant change | no significant change | no change |
| 9 | minor scour | minor scour | coarsened |
| 10 | major fill | major fill | fined |
| 11 | mod. scour | minor scour | no change |
| 12 | minor scour | no significant change | coarsened |
| | | | |
| *Clear-Cut Site* | | | |
| 101 | major scour | major scour | coarsened |
| 102 | major scour | major scour | no change |
| 103 | minor fill | minor fill | no change |
| 104 | minor scour + minor fill | no significant change | coarsened |
| 105 | mod. fill | minor fill | coarsened |
| 106 | minor fill | no significant change | coarsened |
| 107 | major scour | mod. scour | coarsened |
| 108 | major scour | mod. scour | coarsened |
| 109 | minor scour | minor scour | coarsened |
| 110 | mod. fill | minor fill | coarsened |
| 111 | mod. scour | mod. scour | coarsened |
| 112 | mod. scour | mod. scour | coarsened |
| 113 | minor scour | minor scour | coarsened |
| 114 | mod. scour | mod. scour | coarsened |
| 115 | major scour | major scour | no data |
| 117 | no data | no data | coarsened |
| 118 | minor scour + minor fill | no significant change | coarsened |
| 119 | no significant change | no significant change | no change |
| 120 | minor scour | minor scour | coarsened |

[1] "No significant change" indicates an estimated cross-sectional area of scour or fill of less than 1 m². "Minor" indicates changes > 1 m²; "moderate", >2 m²; and "major", >3 m². "Total response" includes scour and/or fill, if signficant; "net response" is the difference between scour and fill.

4.2). Three cross sections (XS 109, 113 and 120) exhibited minor scour, while two others (XS 104 and 118) experienced both minor scour and minor fill for no significant net change. Only one cross section (XS 119) showed no evidence of significant scour or fill. Four cross sections exhibited moderate (XS 105, 110) or minor (XS 103, 106) fill.

Channel scour within the clearcut reach was not uniformly distributed, but occurred in two distinct zones (Figure 4.7[b]). The upper scour zone extended at least 25 to 30 m downstream from the concrete flume for the gaging station (Figure 3.2), where XS 101 and 102 both experienced major scour and a transition from alluvial channel in 1995 (predominantly cobble with no exposed bedrock) to a channel underlain by bedrock under most of its low-flow wetted perimeter in 1996. No bedrock is exposed below a few meters downstream of XS 102. Channel scour in this zone (especially XS 101) may be influenced by the presence of the gaging station flume, which creates the deepest pool (immediately downstream of the flume, Figure 4.1) in the 800 m of surveyed channel.

Immediately downstream of the upper scour zone, a zone of minor net deposition to no net change extends from XS 103 to XS 106, a distance of approximately 40 m (Figure 4.7[b]; Table 4.2). A second and longer zone of channel scour extends for at least 100 m between XS 107 and 115 (Figure 4.7[b]; Table 4.2). One cross section within this zone (XS 110) exhibited minor net fill, but 5 of the 7 other cross sections in this sub-reach exhibited moderate to major scour and the remaining 2 exhibited minor scour. It is difficult to say whether this scour zone extended farther downstream than XS 115, since XS 116 was abandoned after 1990 and the location of one end of XS 117 appears to have been moved in 1996 (field notes give no indication of a post being replaced), but XS 118 (about 40 m downstream of XS 115) and XS 119 exhibited no significant net change (Table 4.2). Cross section 120 showed minor net scour.

In general, the old-growth cross sections revealed a pattern of substantial aggradation upstream of channel-spanning LWD structures and minor to moderate scour downstream of and between these structures. All three cross sections immediately upstream of channel-spanning LWD within this reach (XS 3, 7 and 10)

**(a) Old-Growth (MAC) Site**



**(b) Clearcut (MCC) site**
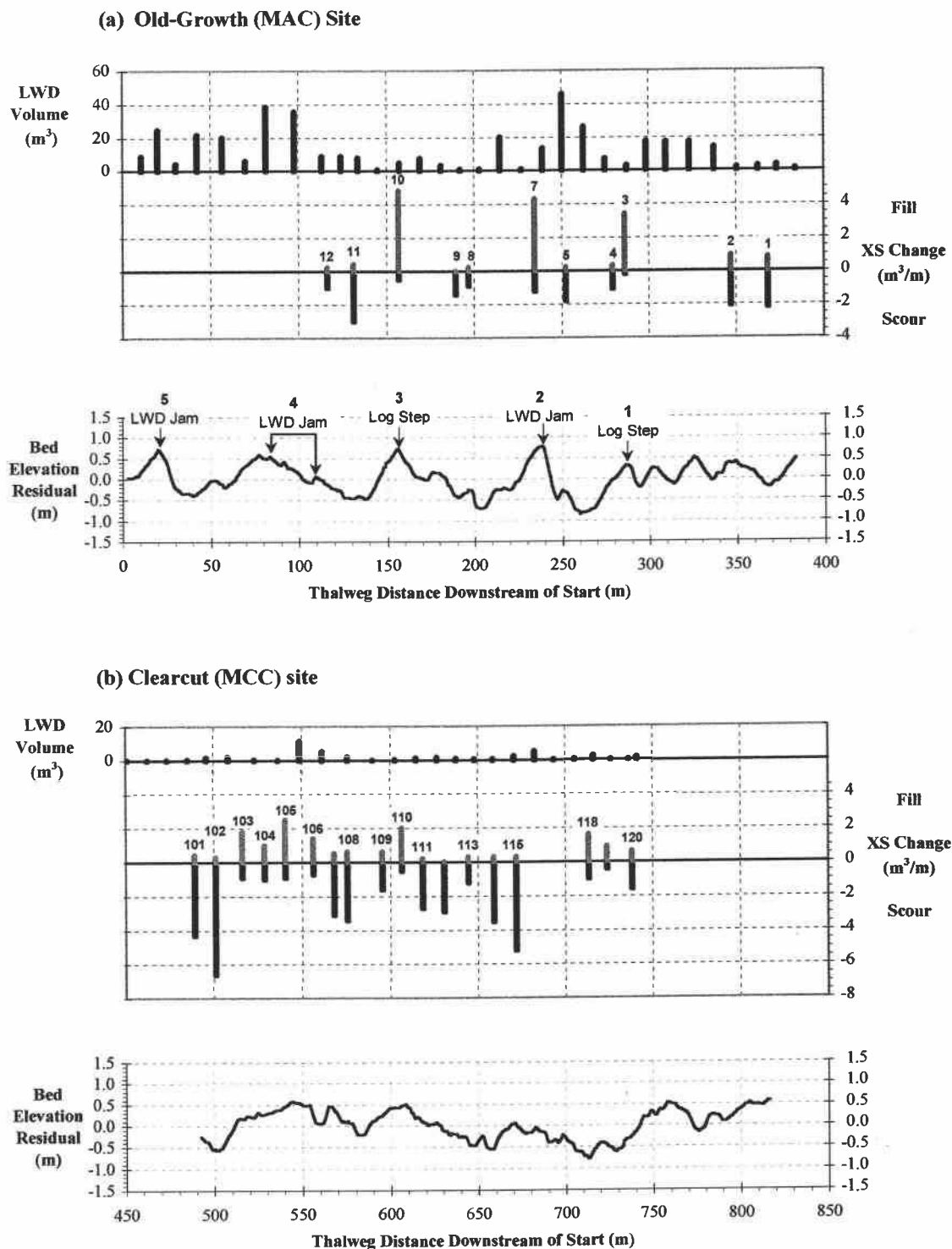


Figure 4.7. Longitudinal plot showing volume of in-channel LWD, cross section scour and fill, and bed elevation residual for the Mack Creek cross section sites: (a) old-growth site; (b) clearcut site.

exhibited substantial aggradation in response to the February 1996 flood (XS 7 also exhibited minor scour), while three other cross sections not closely associated with existing LWD structures (XS 1, 2 and 11) experienced moderate to major scour. Five of the six remaining cross sections exhibited minor scour (XS 4, 5, 9, and 12) or no significant change (XS 8). (Scour and fill volumes could not be calculated for XS 6, which crosses the lower LWD jam in the old-growth reach at a diagonal (Figure 3.2), because the position of a significant fraction of the channel bottom could not be determined in 1995 due to the presence of a suspended log parallel to the cross section line.)

Aggradation at XS 3 and 7 was the result of deposition upstream of existing structures, but aggradation at XS 10 resulted from accumulation of sediment behind a single channel-spanning log that was deposited immediately downstream of XS 10 during the February 1996 flood (Figures 3.2, 4.2). According to the LWD database, this log (#O403) moved from a position anchored on the bank and oriented parallel to the channel (completely outside the low-flow channel but wholly within the bankfull channel and 50% above bankfull stage) to a new position a few meters downstream perpendicular to and spanning the channel, 80% within the low-flow channel and 100% below bankfull stage.

At the reach scale, based on average cross section responses, old-growth and clearcut sites exhibited essentially the same overall magnitude of total scour and fill, but substantially different degrees of *net* channel change (Figure 4.8). The old-growth site exhibited nearly identical amounts of scour and fill overall, resulting in negligible net erosion or deposition within this reach, while cross sections at the clearcut site experienced more scour and less fill, with the net result that substantial net scour occurred within this reach (Figure 4.8). Due to the large variability of the individual cross section responses, these differences are not statistically significant, but the differences in scour and net change are nearly so at a significance level of 0.05 (note 95% confidence intervals in Figure 4.8).
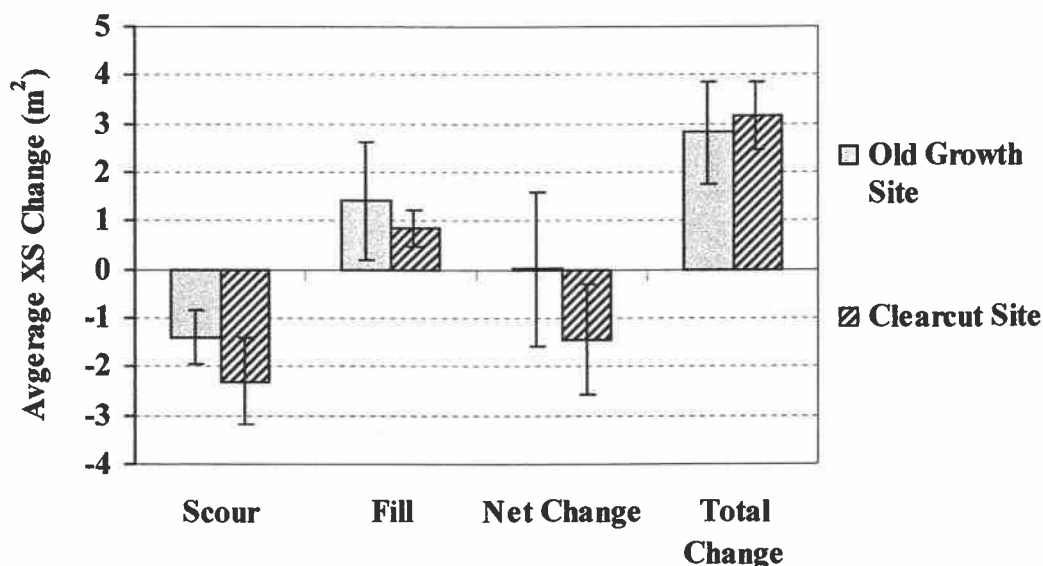
Figure 4.8. Comparison of average 1995-96 cross section changes at the Mack Creek old-growth and clearcut sites. Error bars show 95% confidence interval.

### 4.2.2   CROSS SECTION RESPONSE IN RELATION TO INPUTS OR MOVEMENT OF LWD

Because LWD has been widely reported to be an important mechanism for sediment storage in mountain streams (Megahan and Nowlin, 1976; Megahan, 1982; Nakamura and Swanson, 1993; Thompson, 1995), it was hypothesized that increases in in-channel LWD would tend to be associated with channel aggradation or fill, while decreases in LWD in the channel would tend to be associated with channel scour. More crudely, it was hypothesized that larger cross section changes would be associated with locations where there was significant movement or new inputs of LWD than locations where LWD changes were absent. However, the data do not strongly support either hypothesis. Changes in distribution of LWD volume within the channel (zones 1 to 3) between 1995 and 1996 were not spatially correlated with cross section changes for the same period (Figure 4.9 [a]). Neither the direction of cross section change (i.e., scour vs. fill) nor its magnitude bore any consistent relationship to changes in LWD volume in the channel in the immediate vicinity of the cross section. Of the cross sections that experienced the greatest scour (XS 1, 2, and 11) or fill (XS 3, 7 and 10), only two (XS 2 and 7) were proximal to large changes in
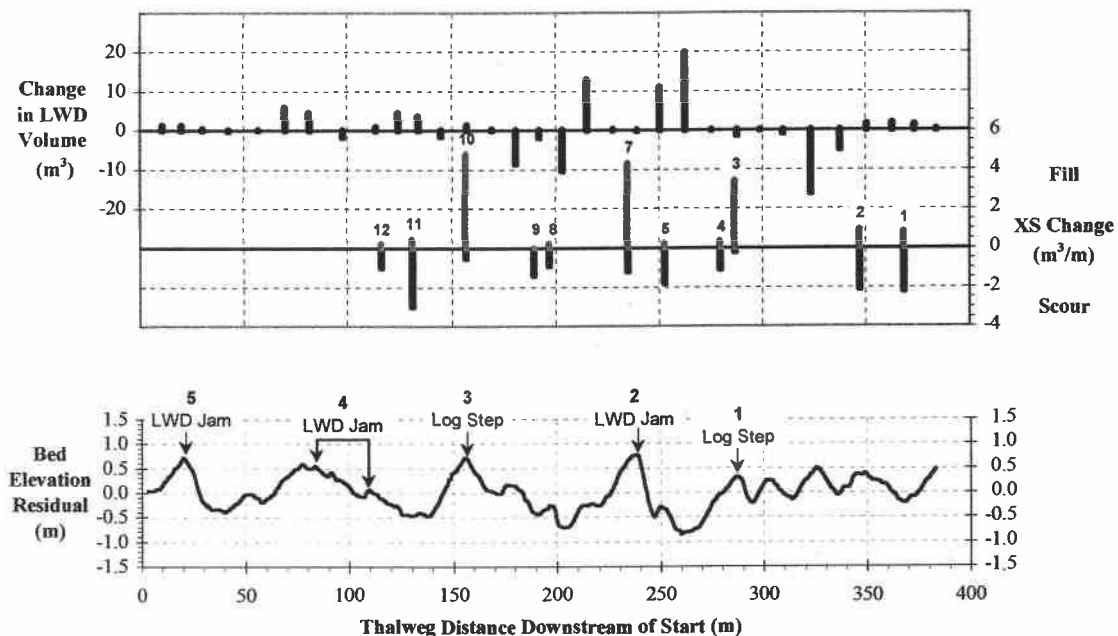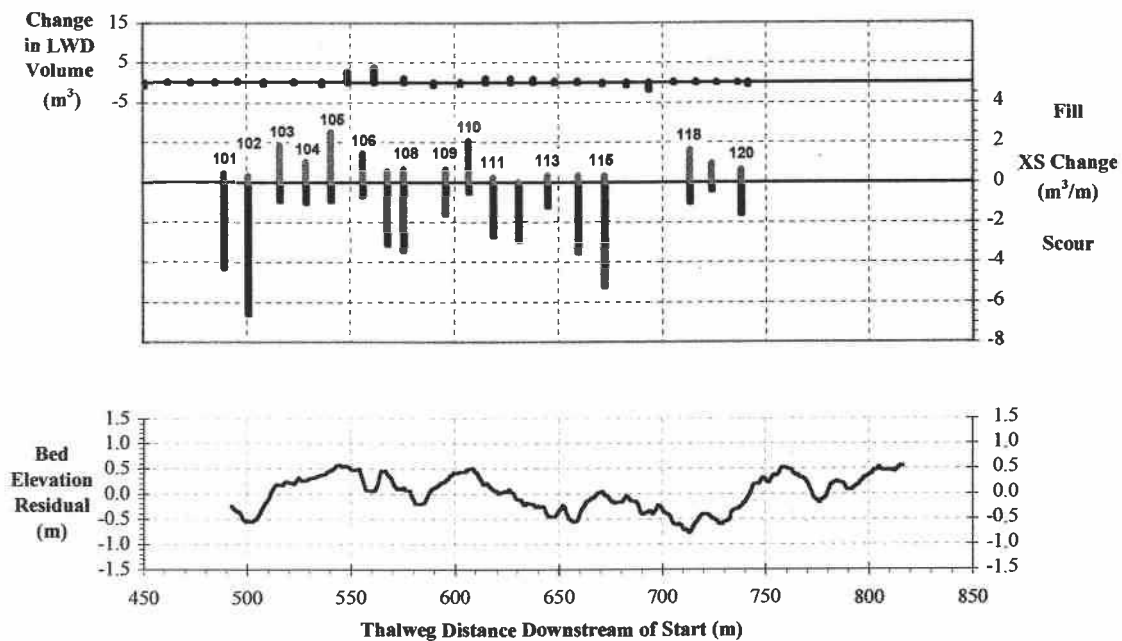
Figure 4.9. Longitudinal plot showing 1995-96 change in volume of in-channel LWD, cross section scour and fill, and bed elevation residual for the Mack Creek cross section sites: (a) old-growth site; (b) clearcut site.

LWD volume within the channel (Figure 4.9 [a]). Partial dismantling of a channel-spanning LWD accumulation at the head of a mid-channel bar just upstream of XS 2 in the 1996 flood may have contributed to scour at XS 2, while accumulation of additional LWD by the LWD jam immediately downstream of XS 7 may have contributed to aggradation at XS 7. (Scour at XS 1 may be related to a removal of a 10-ft diameter culvert 30 m downstream of in September 1994 to improve fish passage and prevent mass failure of the road fill [Gregory, personal communication]. Approximately 1200 to 1500 cubic yards of sediment were excavated from the channel at that time [Cissel, personal communication].) In the clearcut reach, there was little LWD in the channel to start with and hence little redistribution of LWD volume. Thus, channel changes in the clearcut reach clearly were not driven by redistribution or new inputs of LWD (Figure 4.9 [b]).

The longitudinal pattern of channel slope as revealed by thalweg elevation residual appears to be a much better predictor of cross section change than either the LWD volume in the channel or the change in LWD volume in the channel before and after the flood (Figures 4.7, 4.9). Channel scour in 1996 was observed principally at locations where channel gradient is greater than the reach average (XS 5, 8, 9 and 12 in the old-growth and 101, 107, 108 and 111-113 in the clearcut) or at concave-upward inflection points in the longitudinal profile where channel slope decreases abruptly (old-growth XS 1 and 11 and clearcut XS 102 and 114). Channel fill was observed at convex-upward inflection points in the longitudinal profile (sections 3, 7, 10, 106, and 110) and where channel gradient was less than the reach average (sections 103-105). Exceptions to this pattern were XS 2 and 115, both of which are located at convex-upward inflection points yet experienced scour rather than aggradation.

### 4.2.3   PARTICLE SIZE RESPONSE

The old-growth and clearcut reaches exhibited strikingly different bed material texture responses to the February 1996 flood, both at the reach and within-reach scales. At the reach scale, the old-growth reach exhibited negligible change in its bed
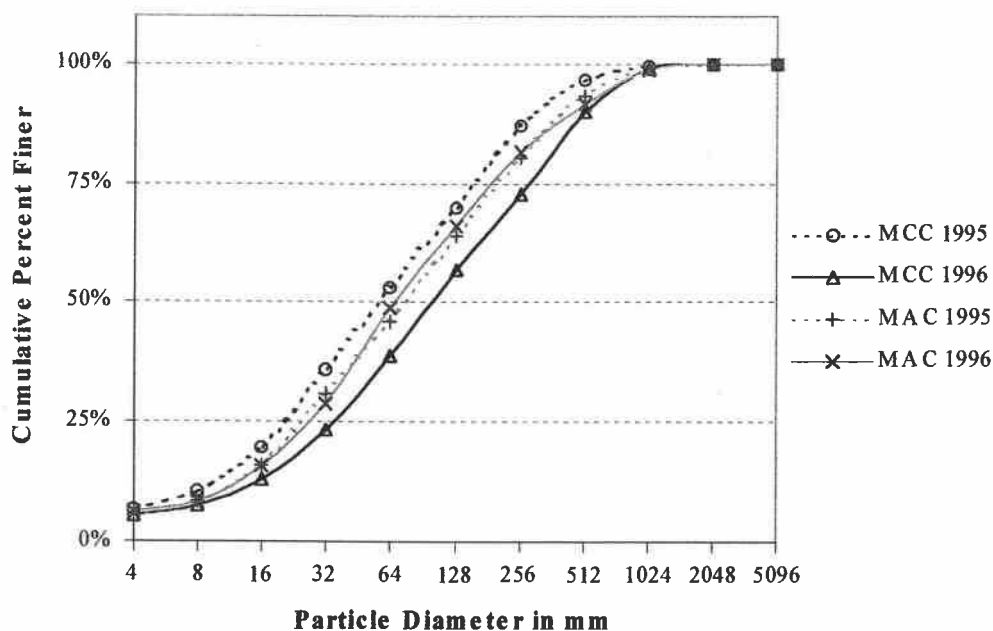
Figure 4.10. Cumulative particle size distribution for the Mack Creek old-growth (MAC) and clearcut (MCC) sites for 1995 and 1996. Plots were created using pooled data from all cross sections at each site.

surface particle size distribution, while the clearcut reach exhibited pronounced coarsening (Figure 4.10). This coarsening in the clearcut reach was significant for all size fractions (Table 4.3), and was more consistent and uniformly distributed than the cross section response within the reach (Table 4.2). Nearly all the cross sections within the clearcut reach exhibited a discernible increase in particle size, and none exhibited a decrease in particle size. In contrast, cross sections in the old-growth reach exhibited a mix of coarsening and fining, with most of the latter occurring upstream of LWD structures (XS 3 and 10; Table 4.2).

At the reach scale, differences in bed surface particle size distribution between the old-growth and clearcut sites were greater after the February 1996 flood than they were prior to this flood. The cumulative distribution curve for both sites had a similar shape in both 1995 and 1996, indicating roughly the same degree of sorting, but the clearcut site had somewhat finer bed surface than the old-growth site in 1995 and a coarser distribution in 1996 (Figure 4.10). The differences between the two sites in the average median ($D_{50}$) and $D_{84}$ particle size at the cross section locations were not

Table 4.3.  Selected 1995 and 1996 particle size statistics (in millimeters) for the old-growth and clearcut sites.  Indicated p-values for between-year comparisons are from a paired t-test, using log-transormed data,  of the hypothesis that the mean difference between 1995 and 1996 values is zero, with the alternative hypothesis that the difference is nonzero; values of 0.05 or less are shown in **boldface**.  The p-values in the bottom row of the table are from a two-sample t-test, also using log-transformed data, for a difference between sites in a given year.

| Site | Parameter | n | $D_{84}$ 1995 | $D_{84}$ 1996 | $D_{50}$ 1995 | $D_{50}$ 1996 | $D_{16}$ 1995 | $D_{16}$ 1996 |
|------|-----------|---|------|------|------|------|------|------|
| MCC | mean | 17 | 224 | 396 | 60.9 | 95.0 | 14.5 | 20.4 |
| | 95% C.I. | | 186-269 | 363-432 | 49.7-74.7 | 83.2-108 | 12.2-17.2 | 17.3-24.0 |
| | p-value | | **<0.0001** | | **0.0026** | | **0.0136** | |
| MAC | mean | 11 | 280 | 273 | 80.9 | 68.9 | 19.3 | 19.1 |
| | 95% C.I. | | 198-394 | 179-414 | 57.4-114 | 48.2-98.6 | 14.2-26.4 | 14.3-25.5 |
| | p-value | | 0.8821 | | 0.3136 | | 0.9163 | |
| MCC vs. MAC | p-values | | 0.1454 | **0.0195** | 0.0864 | **0.0325** | **0.0476** | 0.6073 |

statistically significant in 1995 (2-sided p-value of >0.05), but *were* significantly different in 1996 (Table 4.3, bottom row).  The average $D_{16}$ value based on the individual cross section samples was not significantly different between the sites in 1996, but was significantly different in 1995 (*greater* in the old-growth reach than in the clearcut reach).  (Note that Figure 4.10 and Table 4.3 show somewhat different $D_i$ values because Figure 4.10 is based on a composite sample of all cross sections at a site, while Table 4.3 counts each cross section as a separate sample to maintain enough degrees of freedom to permit statistical testing).

The finding that the bed material was slightly finer in the clearcut reach than in the old-growth reach in 1995 (Figure 4.10) was contrary to the expectation that there would be more relatively fine bed material (i.e., gravel and small cobbles) in the old-growth reach due to the increased hydraulic roughness and sediment storage capacity associated with LWD.  It is possible that the streambed in the clearcut reach was anomalously fine in 1995 due to release of a wedge of fine sediment upstream up the

road crossing (Figure 3.2) when the culvert formerly at that location was removed and replaced by the current bridge in September 1994 (Gregory, personal communication). If so, the coarsening observed in the clearcut reach in association with the February 1996 flood could be partially a result of channel adjustment to this prior disturbance. Unfortunately, particle size data were not collected in association with the cross section surveys prior to 1995, so it is impossible to tell whether or to what degree bed texture in the clearcut reach was affected by release of stored fine sediment due to removal of the culvert. The cross section data for the clearcut reach, however (Appendix B), do not show any evidence of significant, widespread aggradation between 1990 and 1995 that would indicate a substantial influx of gravel to the reach.

The largest patches of relatively fine, readily transportable bed material (gravel and small cobbles) were typically observed just upstream of log steps and LWD jams (Figures 4.2, 4.4). This observation is supported by the particle size data. Cross sections located immediately upstream of channel-spanning LWD structures tended to have significantly finer bed material, particularly at the coarse end of the size distribution, than the reach as a whole. Cross sections located immediately downstream of LWD structures tended to have bed material somewhat coarser than the reach average (Figure 4.11). The fining effect of LWD structures on upstream particle size was particularly pronounced. In the 2 post-flood years (1996 and 1997), the three cross sections located upstream of LWD structures (XS 3, 7 and 10) had the smallest $D_{84}$ values of all 12 old-growth cross sections (Appendix A).

## (a) 1995

Summary of Particle Size Statistics--1995

| Section No. | $D_{84}$ | $D_{50}$ | $D_{16}$ |
|---|---|---|---|
| _Upstream of LWD_ | | | |
| 3 | 152 | 35 | 8 |
| 7 | 234 | 92 | 11 |
| | | | |
| **Combined** | **205** | **64** | **9** |
| _Downstream of LWD_ | | | |
| 5 | 558 | 189 | 30 |
| 12 | 105 | 36 | 13 |
| **Combined** | **322** | **64** | **16** |
| _Entire Reach_ | _302_ | _77_ | _17_ |
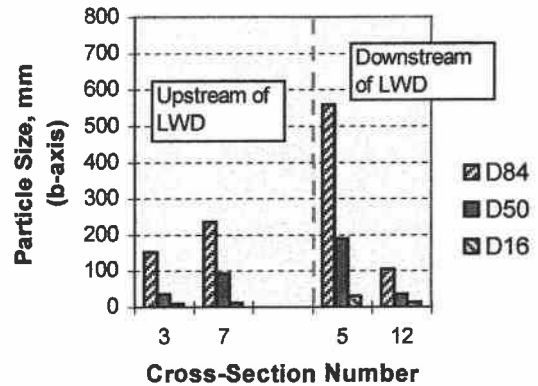


## (b) 1996

Summary of Particle Size Statistics--1996

| Section No. | $D_{84}$ | $D_{50}$ | $D_{16}$ |
|---|---|---|---|
| _Upstream of LWD_ | | | |
| 3 | 136 | 27 | 7 |
| 7 | 184 | 64 | 17 |
| 10 | 84 | 35 | 15 |
| **Combined** | **136** | **40** | **11** |
| _Downstream of LWD_ | | | |
| 5 | 494 | 95 | 19 |
| 12 | 251 | 61 | 16 |
| **Combined** | **408** | **67** | **16** |
| _Entire Reach_ | _302_ | _66_ | _16_ |
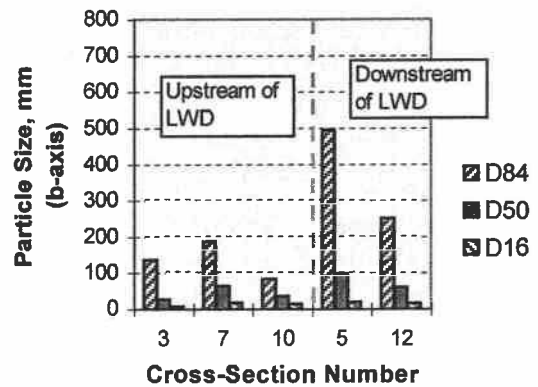


## (c) 1997

Summary of Particle Size Statistics: 1997

| Section No. | $D_{84}$ | $D_{50}$ | $D_{16}$ |
|---|---|---|---|
| _Upstream of LWD_ | | | |
| 3 | 222 | 54 | 11 |
| 7 | 250 | 80 | 14 |
| 10 | 190 | 72 | 21 |
| **Combined** | **222** | **65** | **14** |
| _Downstream of LWD_ | | | |
| 5 | 803 | 211 | 62 |
| 12 | 400 | 81 | 10 |
| **Combined** | **625** | **147** | **22** |
| _Entire Reach_ | _370_ | _98_ | _21_ |
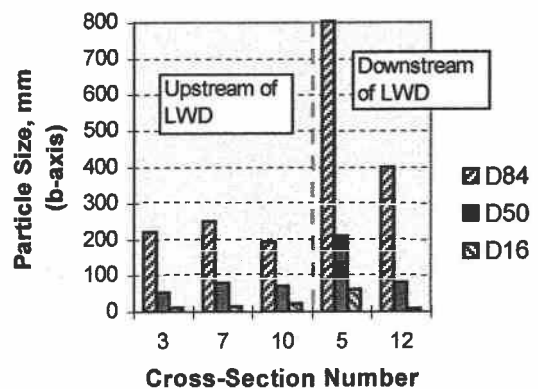


Figure 4.11. Bed surface particle size at cross sections located within one channel-width upstream and downstream of LWD structures, MAC site: (a) 1995; (b) 1996; (c) 1997. Values for "Entire Reach" are for pooled samples and differ from those shown in Table 4.3, which are averages of $D_i$ values for individual cross sections.

## 5 Discussion

### 5.1 Geomorphic Functions of Static and Moving LWD

LWD influences channel morphology and channel change principally by promoting or retarding channel bed scour or bank erosion, promoting deposition and anchoring sediment, or some combination of these effects. Key LWD pieces can influence channel and flow geometry individually or in accumulations. Borrowing from Nakamura and Swanson (1993), a key piece is defined here as a LWD piece that anchors a significant sediment accumulation or is a structural member of a LWD jam and which is large enough to span the main channel at constrictions. A potential key piece is a LWD piece which is large enough to function as a key piece but which does not currently anchor a sediment accumulation or form part of a LWD jam. The most geomorphically effective LWD (in terms of influencing channel form and sediment transport) are key pieces which form channel-spanning log steps or LWD jams, which can significantly modify both channel pattern and longitudinal profile. Marginal LWD pieces and accumulations can also influence channel geometry locally and anchor limited marginal sediment accumulations.

Most previous work on LWD interaction with channel morphology has focussed primarily on the role of stationary LWD accumulations within the channel. Such *static LWD*—individual pieces or accumulations that remain in place but can interact dynamically with flow and sediment—can influence both present channel morphology and temporal patterns of channel adjustment (Nakamura and Swanson, 1993). However, it is also important to consider the role of LWD as a dynamic structural element of the channel. *Dynamic LWD* can be defined as individual pieces that move or that enter the channel during a particular event or specified time period. It also includes LWD structures that are formed, substantially expanded, or partially or completely dismantled during the specified event or time period. LWD that moves during a particular event can interact with sediment and affect channel morphology at both the old and new locations.

Major static and dynamic effects of individual key pieces and LWD jams in intermediate size streams such as Mack Creek, which are capable of occasionally redistributing at least some fraction of their key LWD, are summarized in Table 5.1. Both channel-spanning individual key pieces that form log steps (requiring a relatively horizontal orientation) and LWD jams can accumulate an upstream sediment wedge, divert flow laterally to cause bank erosion, widen the channel through bank erosion or sideslope failure and channel filling, and cause upstream fining and downstream coarsening of the bed surface. But LWD jams appear to have a greater tendency to cause channel widening (Table 4.1), and also are probably more dynamic sediment storage sites than log steps. Once a flat-lying channel-spanning key piece begins to trap sediment, it tends to quickly become buried on the upstream side, raising the bed of the stream and establishing a new local base level (Figure 4.2). Log steps are particularly stable sediment storage sites similar in function to check dams. LWD jams, on the other hand, tend to be both higher and "leakier" than log steps. The crest of LWD jams typically protrudes well above the bed (Figures 4.3, 4.4), unlike log steps in which the step crest typically is part of the bed, at least partially submerged even at low flow. The arrangement of the key pieces, or of smaller LWD and organic debris which regulate the permeability of the LWD jam to water and sediment, may shift from time to time, causing release of stored sediment or additional sediment impoundment. Time-lapse photography at two locations upstream of LWD jams (features 2 and 4 in Figure 3.2) and anecdotal observations of researchers who have worked at Mack Creek over a 20-year period confirm that the channel immediately upstream of LWD jams is a particularly dynamic environment (Gregory, personal communication).

## 5.2 Influence of LWD on Channel Characteristics

Channel-spanning LWD structures—log steps and LWD jams—create pronounced steps in the longitudinal profile (Figure 4.1). These structures create upstream low-gradient or backwater hydraulic environments (depending on flow) which constitute particularly stable sediment storage sites where bed material tends to

Table 5.1. Effects of static and dynamic LWD on channel morphology and channel adjustment in high-gradient streams of intermediate size.

| Type of Structure | Static Effects | Dynamic Effects |
|---|---|---|
| Channel-spanning key piece | • Accumulate upstream sediment wedge, causing aggradation and moderate to long-term sediment storage.<br>• Divert flow laterally into bank, promoting bank erosion and scour<br>• If suspended, anchor marginal sediment and/or OD accumulation on lower end, and possibly cause enhanced scour and pool formation beneath or downstream of suspended portion<br>• Promote upstream fining and possibly downstream coarsening of bed material. | Same as static effects, plus:<br>• Channel degradation associated with removal of step-forming log.<br>• Channel-margin scour associated with removal of a log anchoring a marginal sediment/OD accumulation |
| LWD jam | • Accumulate large sediment wedge, causing substantial local aggradation.<br>• Periodically release sediment, causing upstream scour and deep pool formation.<br>• Widen channel through bank erosion and sediment deposition.<br>• Periodically shift main thalweg from side to side of upstream sediment wedge, causing local scour and fill within the channel.<br>• Promote upstream fining and possibly downstream coarsening of bed material. | Same as static effects, plus:<br>• Major degradation with upstream and downstream scour when jam blows out. |
| Marginal key piece or LWD accumulation | • Create/stabilize marginal bars and OD accumulations, typically upstream of piece.<br>• Protect/stabilize existing mid-channel bar (downstream of piece) | Same as static effects, plus:<br>• Destabilize marginal or mid-channel bar when floated out; promote local scour.<br>• Block side-channel entrance, promoting sediment deposition in and/or abandonment of side channel.<br>• Reactivate and scour side channel when LWD accumulation at channel entrance is washed out. |

be finer than elsewhere in the channel (Thompson, 1995). This type of hydraulic environment can be of particular importance to aquatic organisms (Statzner et al., 1988).

Although log steps (Figure 4.2) are smaller structures than LWD jams (Figure 4.3), both have a similar magnitude of effect on the longitudinal profile of Mack Creek at the old-growth site (Figure 4.5[a]). On a longitudinal bed elevation residual plot, peaks associated with log steps have similar height but somewhat shorter, steeper rising limbs compared with peaks associated with LWD jams. Thus, the log steps have lower-gradient channel upstream than do the LWD jams, but this effect does not extend as far upstream as it does for jams. It is worth noting that while LWD jams do show up as peaks in a longitudinal plot of in-channel LWD volume (top plot in Figure 4.7[a]), log steps do not, despite their obvious geomorphic significance. Thus, longitudinal surveys of LWD loading (number of pieces, volume, or mass of LWD per unit channel length or area) alone are not sufficient to predict or characterize the effects of LWD on channel morphology, at least not on a local scale.

Particle size sample results from this study are consistent with previous studies that have shown that LWD provides depositional sites for finer bed material (e.g., Beschta, 1979; Bilby, 1981; Thompson, 1995). In particular, bed material particle size sampled within one channel-width upstream of channel-spanning LWD structures in the old-growth reach at Mack Creek was consistently finer than the reach-average particle size across the entire particle size distribution ($D_{84}$, $D_{50}$, $D_{16}$) for all three years (1995-97) in which particle size was sampled (Figure 4.11). At the reach scale, the influence of LWD on particle size is less clear. As reported in Section 4.2.3, the bed surface was slightly (but not significantly) finer in the clearcut reach than in the old-growth reach in 1995, but was significantly coarser in the clearcut reach than in the old-growth following the February 1996 flood (Figure 4.10, Table 4.3). The influence of structural LWD on particle size in Mack Creek thus appears to be most significant at a local scale (e.g., the scale of individual cross sections). At the reach scale, the effect of LWD manifests as a greater within-reach variability in particle size, as reflected by field observations (e.g., Figures 4.2 and 4.3) and by the consistently greater coefficient of variation of the $D_{84}$, $D_{50}$, and $D_{16}$ statistics for the old-growth

cross sections vs. the clearcut cross sections for all three years during which particle size data were collected (Appendix A).

## 5.3   Influence of LWD on Channel Response to the Flood of February 1996

Nakamura and Swanson (1993) found that the largest and most frequent cross section changes observed in 5th-order Lookout Creek over a 10-year period (1978-88) were associated with newly input and static key LWD pieces.  The largest changes occurred in the winter of 1981-82, when four old-growth trees fell into a 75-m section of the channel, and during the 1986 water year, when a moderately large (5.5-year recurrence interval) flood occurred.  Thus, it might be expected that the largest cross section changes in Mack Creek in response to the February 1996 flood would be associated with key LWD—in particular, log steps and LWD jams.  This would be consistent with the hypothesis that key LWD increases the local variability in channel response to floods while reducing channel change at the reach scale.

The response of the Mack Creek channel to the February 1996 flood was consistent with these expectations.  Although there was no apparent association between the volume of LWD within the channel and magnitude of cross section change, log steps and LWD jams were clearly associated with substantial upstream deposition in response to the 1996 flood, which produced the largest observed cross section changes in the old-growth reach (Figure 4.7[a]).  At the reach scale, this resulted in a more patchy channel response within the old-growth reach than was observed within the clearcut reach (Figure 4.7).  Thus, the specific arrangement of key LWD within the channel was much more important than variations in the quantity of LWD in determining channel response to the 1996 flood.

The geomorphic function of a key piece may change dramatically even when the piece does not move.  This fact is illustrated by the log step just downstream of XS 3 (Figure 3.2).  The log forming this step is a bigleaf maple toppled by bank erosion that was classified in the LWD database as having 60% of its volume in zone 3 (in the channel above bankfull stage), but as of summer 1996 the log formed part of streambed, with water spilling over it even at low flow.  Without moving, this log

changed over time from being suspended above the channel to forming part of the bed by accumulating a substantial upstream sediment wedge. Thus, because new data on the position and other characteristics of a piece are collected only when the piece is inferred to have moved since the previous survey, major changes in the functional role and importance of key or potential key pieces can go undetected by the LWD inventory surveys.

## 5.4    Influence of LWD on Sediment Storage and Transport

Channel-spanning LWD clearly creates major sediment storage sites within the old-growth reach at Mack Creek. By creating large steps in the longitudinal profile of the channel (Figure 4.1), channel-spanning log steps and LWD jams trap large sediment wedges. Since such LWD accumulations also tend to widen the channel, the volume of sediment that they can store in the upstream wedge is considerable. Thompson (1995) argues that pools upstream of LWD represent particularly stable sediment storage sites; because they represent low-gradient, backwater environments even at high flows, sediment stored in pools upstream of LWD will likely have a longer residence time than sediment stored in scour or plunge pools located downstream of flow obstructions or sediment stored in bars or riffles. No channel-spanning LWD or analogous sediment storage sites are present in the clearcut reach. Thus, it is likely that both the volume and mean residence time of sediment stored in-channel in the clearcut reach are less than in the old-growth reach.

Bedload transport or sediment volume stored in the channel were not measured or estimated in this study. However, the cross section surveys and associated particle size data provide direct evidence of changes in sediment storage and, hence, indirect evidence of sediment transport in the old-growth and clearcut reaches during the winter of 1995-96. These data suggest significant differences in the movement of sediment within the two reaches. In general, the clearcut reach was dominated by channel scour and coarsening of the bed material (Table 4.2), suggesting a net loss of sediment from the reach due to selective transport of finer bed material. In contrast, substantial aggradation (i.e., an increase in sediment storage) occurred at all three

locations in the old-growth reach where cross sections are located immediately upstream of channel-spanning LWD (XS 3, 7, and 10; Table 4.2), accompanied in two of the three locations by a distinct decrease in bed surface particle size. At the reach scale, no significant change in particle size was observed in the old-growth reach between 1995 and 1996 (Figure 4.10, Table 4.3).

The importance of channel-spanning LWD in creating stable sediment storage sites, particularly for relatively fine bedload, is underscored by the fact that all three cross sections in the old-growth reach where aggradation occurred in response to the February 1996 flood were located within one channel-width upstream of a log step or LWD jam. Further, even though this was the largest flood in a 20-year record, both of the pre-existing structures apparently increased their sediment accumulations. In the clearcut reach, where no channel-spanning or geomorphically significant LWD was present, significant but minor net channel fill also occurred at three cross sections (XS 103, 105, and 110; Table 4.2). However, aggradation at these locations was accompanied by coarsening of bed material at all three locations, not fining as in the aggraded old-growth cross sections.

These results and the much more pronounced 1995-96 particle size response (coarsening) in the clearcut reach as opposed to the old-growth reach (Figure 4.10) support the claim that LWD decreases the sediment transport efficiency of a channel (e.g., Heede, 1977; Marston, 1982; Adenlof and Wohl, 1994; Montgomery et al., 1996). Channel-spanning LWD in the old-growth reach at Mack Creek trapped a significant quantity of sediment during the February 1996 flood, and may have been instrumental in preventing more extensive channel scour or a measurable reach-scale textural response to the flood. In the clearcut reach, where channel-spanning LWD is absent, much more extensive channel scour and a measurable reach-scale coarsening of the bed material occurred. We can infer from this that bedload sediment was more efficiently transported through (and out of) the clearcut reach than the old-growth reach. As a result, the clearcut reach was somewhat sediment-starved during the February 1996 flood, to which condition it responded by general down-cutting and coarsening of its channel.

## 5.5    Limitations of Study Design and Recommendations for Future Modifications

Although the two long-term data sets used in this study have a greater length of record and, in the case of the LWD data, are far more detailed than those that have been previously reported in published studies, they nonetheless suffer a number of limitations.  First and perhaps foremost, cross sections may not be the most appropriate tool for monitoring channel change in steep mountain streams.  Since the chief effect of LWD on channel morphology in such streams is the creation or modification of a stepped channel profile (Keller and Swanson, 1979; Nakamura and Swanson, 1993; Thompson, 1995), in which channel structure is predominantly expressed through variations in channel slope and bed texture (Grant et al., 1990; Montgomery and Buffington, 1997), cross section surveys may not adequately characterize the spatial structure or the temporal variation of spatial structure in these streams.  Repeated longitudinal profile surveys might be more appropriate for this purpose, but are inherently less repeatable (hence less readily comparable between years) than cross section surveys.

A limitation more specific to the Mack Creek site is the relatively small number and irregular spacing of reference cross sections, particularly in the old-growth reach.  Additional cross sections upstream of section 12 (Figure 3.2) and more even cross section spacing would have been helpful.  Only two cross sections in the data set (only one before 1996) were located within a channel width or so (i.e., clearly within the sediment accumulation zone) of log steps and only one was located immediately upstream of a LWD jam, while two cross sections were located immediately downstream of LWD jams and none were located downstream of log steps (Figure 3.2).  This limited "sample size" of cross sections having an unambiguous spatial relationship to significant LWD structures severely constrains the usefulness of the cross section data set for evaluating the effects of LWD on channel form and process.

Several difficulties arise from trying to use the cross section and LWD data sets together due to their different spatial structure.  The LWD data are essentially a discretized longitudinal transect derived from data that are inherently two-dimensional

(i.e., the map position and characteristics of LWD within and adjacent to the channel). The cross section data set, on the other hand, are an inherently one-dimensional data set (i.e., bed elevation as a function of cross-channel distance) that is oriented orthogonal to the LWD transect. Further, the spatial grain of the LWD data (which at 10 m is smaller than many individual LWD pieces, which can span multiple segments on the LWD baseline), is coarse relative to that of the cross section data (0.5 m). For example, sub-grain (hence, undetectable) LWD movement, such as pivoting of a single large log, might induce significant changes in a cross section profile. Also, since the spatial grain of the LWD data is not much smaller than the spacing between cross sections (i.e., the grain of the cross section data for between-section comparisons), and since a cross section can fall anywhere between the upstream and downstream boundaries of a LWD baseline segment, the spatial relationship between individual cross sections and LWD data points is inexact and variable. These problems become less significant at greater spatial scales. Thus, there is little problem relating LWD and cross section data at the reach scale (i.e., old-growth vs. clearcut reach), but relating them at the scale of individual cross sections to make between-section comparisons becomes more problematic, and the LWD data are of little value for explaining within-section changes.

These considerations suggest some modifications to the current monitoring program that could improve the usefulness of the data collected. Cross section locations should be selected to sample a representative selection of channel environments based on channel unit type (e.g., pool, riffle, etc.) and LWD influence. For example, cross sections could be established in the zones of up- and downstream influence of existing log steps and LWD jams—say, within a distance of one-half of the active channel width up- or downstream of these structures. More regular, frequent spacing of cross sections within the old-growth reach, at a spacing of approximately one active channel width as in the clearcut site, would ensure a reasonably representative sampling of different channel environments within the reach even when LWD is rearranged and channel units are changed by future floods.

Because channel configuration and LWD influence can change over time, changes in these characteristics should be noted when cross sections are resurveyed.

The channel unit type and local channel slope—measured over the length of the channel unit containing the cross section or over a fixed distance such as 5 m (roughly one-half the average active channel width) up- and downstream of the cross section line—should be measured and recorded each time the cross sections are surveyed. During the annual LWD inventory, changes in the function of a piece of LWD or its position relative to the channel should be noted even when there is little or no movement of the piece. For example, if a log that was perpendicular to the channel is pivoted to a position against the bank, or a log which was suspended above the channel captures a wedge of bedload to become a log step, these are important changes that should be recorded.

# 6   Conclusions

Log steps and LWD jams create distinctive, 1.5- to 3-m high steps in the channel profile of Mack Creek, accounting for about 30% of the total channel relief in the old-growth reach and zero percent in the clearcut reach. Log steps and LWD jams increase the variability in local channel width, slope, and bed surface particle size, providing diverse physical habitat that may be important to aquatic organisms. Bed material size and channel slope are both reduced upstream of channel-spanning LWD structures. In Mack Creek, which has an average longitudinal valley floor slope of 9.7%, 23% of the channel length within the old-growth reach has a local slope (measured at a scale approximating the average channel width) of 5% or less, compared with just 7.5% of the channel in the clearcut reach.

LWD jams are correlated spatially with locally increased channel width and frequency of large, immobile boulders exposed in the bed. Many of these large boulders are probably immobile even during extreme floods, and may represent relict deposits from non-fluvial processes (e.g., glaciers, debris flows, or landslides). These immobile boulder lag deposits may underlie much of the streambed where bedrock is not exposed, but are exposed downstream of LWD jams and buried upstream.

Channel-spanning LWD structures provide an important mechanism for energy dissipation (Marston, 1982). Acting as large roughness elements in the channel that create diverse hydraulic environments (Gippel, 1995; Lisle, 1995), log steps and especially LWD jams increase reach-scale channel stability while increasing local spatial variability in channel response to particular flood events. The response of Mack Creek to a large flood in February 1996 with an estimated recurrence interval of 23.5 years is consistent with this hypothesis. The clearcut reach exhibited predominantly channel scour and pervasive coarsening of the channel bed. In the old-growth reach, in contrast, the magnitude and extent of channel scour were less, scour was interspersed with substantial aggradation upstream of LWD structures, and bed surface particle size changes were mixed. The old-growth reach also exhibited a finer spatial scale of variation (i.e., more frequent transitions between scour and fill or coarsening and fining; see Table 4.2) than did the clearcut reach.

Log steps and LWD jams are a major control on sediment storage and transport in Mack Creek.  During the February 1996 flood there was substantial movement of bed material in both the old-growth and clearcut reaches, as indicated by the large observed changes at cross section locations.  However, the average net change (total fill minus total scour) for the old-growth cross sections was only $-0.05$ m$^3$/m, while for the clearcut cross sections it was $-1.50$ m$^3$/m (Figure 4.8), suggesting that a significant quantity of sediment was lost from storage within the clearcut reach but that no net change in storage occurred within the old-growth reach.

Cross sections and longitudinal surveys of LWD abundance and size distribution are commonly used tools for assessing interactions between LWD and channel morphology and process, but they are not necessarily the best tools for this job, depending upon the channel gradient and the spatial scale of interest.  In high-gradient, narrow mountain streams, channel structure and variability is primarily expressed along a longitudinal vertical plane through the development of a stepped longitudinal profile, which limits the usefulness of channel cross sections.  While the influence of LWD on channel structure and channel change at the reach scale depends largely upon the quantity and size distribution (relative to channel width) of LWD in the channel, at finer scales it depends critically upon the location, arrangement and structure of LWD within the channel.  Thus, detailed information about the spatial arrangement and geomorphic function or context of individual LWD pieces and accumulations is critical to understanding LWD-channel interaction at sub-reach scales.

## Part II: Frequency, Magnitude, and Spatial Patterns of Channel Response to Peak Flows in a Mountain Watershed

## 7  Introduction

Mountain streams comprise the headwaters of most major river systems. They generate floods, provide sediment and wood to downstream rivers, and serve as refuges or critical habitat for many species, both aquatic and terrestrial. In the Pacific Northwest, they frequently occupy watersheds that provide timber products and/or water supply for downstream users. Understanding mountain stream channel response to natural or anthropogenic stresses (e.g., floods or changes in streamflow or sediment load) is relevant to all these functions.

The morphology and dynamics of mountain streams differ markedly from those of lowland streams, but until recently have been much less well studied (Grant and Swanson, 1995). Whereas large, low-gradient streams have channels and associated valley floor landforms shaped almost entirely by fluvial processes and are able to rework their channels at least every one to two years (Wolman and Miller, 1960), high-gradient mountain streams are strongly influenced by processes and landforms external to the channel (Grant et al., 1990; Grant and Swanson, 1995). Extreme storms trigger mass movements such as landslides and debris flows, which leave lasting impacts on valley landforms in mountainous environments (Hack and Goodlett, 1960; Wolman and Gerson, 1978; Nolan and Marron, 1985; Swanson et al., 1985). However, mountain stream channels are also subject to gradual, prolonged external influences, notably impingement upon the active channel by alluvial fans and large, slow-moving earthflows (Vest, 1988). These can constrain the channel laterally, influence up- and downstream channel gradient, and deliver coarse sediment and boulders that the stream can move only infrequently during unusually large flows (Wolman and Miller, 1960; Grant, 1986; Grant et al., 1990). Bedrock also plays an important role in controlling channel and valley floor morphology in mountain streams (Lisle, 1986; O'Connor et al., 1986; Grant et al., 1990). Hence, changes in mountain

stream channel and valley floor morphology are both episodic and continuous, and depend strongly upon the character of the valley floor and the surrounding landscape.

Stream channels and adjacent valley floor surfaces in mountain watersheds are strongly affected by hillslope processes that deliver particulate matter—i.e., sediment, wood, and organic debris over a wide range of sizes—to the channel. These include slow, chronic or continuous processes such as particle-by-particle transport by surface erosion; slow, continuous downslope bulk movement of soil and weathered bedrock by creep; movement of soil, rock and organic material associated with uprooting and downhill sliding of trees (root throw); and slow, deep-seated downslope displacement of large masses of soil and weathered bedrock by earthflows (Swanson et al., 1982a). Detachment and rapid downslope transport of soil, trees and other organic debris— alternately termed debris avalanches or debris slides—can initiate debris flows in small, steep, low-order channels or deliver large pulses of sediment and organic matter directly to larger channels (Swanson et al., 1987). Debris flows (also called debris torrents) are rapid channelized mass movements of water, sediment, and organic matter which can scour low-order channels to bedrock and deliver large volumes of material (up to 10,000 $m^3$ or greater) to larger streams or to depositional sites within $2^{nd}$ - to $3^{rd}$-order channels or on alluvial fans or valley floors (Swanston and Swanson, 1976; Swanson et al., 1982a; Swanson et al., 1987). Debris slides and debris flows are episodic processes that occur only in association with large storms, delivering large pulses of sediment and organic material to stream channels at many locations within single watershed (Swanson and Dyrness, 1975; Grant, 1986; Nakamura et al., in press; Snyder, in preparation).

These processes do not operate uniformly within a watershed. Their spatial distribution upon the landscape is controlled by topography, geology, and channel network structure, and has important consequences for the morphology and dynamics of mountain stream channels (Grant et al., 1990; Grant and Swanson, 1995; Montgomery and Buffington, 1997; Montgomery, 1999), and for stream and riparian ecosystems (Swanson et al., 1998). Within mountain watersheds, strong contrasts in channel morphology and the dynamics of channel disturbance occur between steep, confined low-order tributaries and larger mainstem ($4^{th}$ to $5^{th}$-order) streams. Low-

order tributaries are strongly coupled to adjacent hillslopes, where tree fall and hillslope mass movements such as landslides and earthflows can deliver material to the stream that it is incapable of moving even at high flows (Scott and Gravlee, 1968; Grant, 1986; O'Connor et al., 1986; Grant et al. 1990). Larger (4th- to 5th-order) mainstem streams, like lowland streams, typically are bordered at least in places by alluvial valley floor landforms such as floodplains and terraces which insulate them to some degree from the valley walls and associated mass wasting processes (Grant and Swanson, 1995; Montgomery and Buffington, 1997).

Montgomery and Buffington (1997) have suggested that a gradient of increasing dominance of fluvial processes in the downstream direction occurs within mountain watersheds as one moves from steep colluvial channels where channel formation is controlled principally by debris flows (Benda, 1990; Seidl and Dietrich, 1992) to lower gradient alluvial channels in which fluvial processes are dominant. Building upon the ideas of Gilbert (1877, 1914, 1917), Lane (1955) and Schumm (1969), they propose that channel morphology reflects an adjustment to the ratio, $q_r$, of transport capacity ($Q_c$) to sediment supply ($Q_s$). Specifically, they postulate that mountain stream channels adjust their beds to achieve an equilibrium in response to a systematic downstream decrease in $q_r$. Their conceptual framework implies a general downstream progression from very high-gradient "source" reach types dominated by hillslope and non-fluvial processes ($q_r \ll 1$) to moderate-to-high gradient "transport" reach types ($q_r \gg 1$) and lower gradient "response" reach types ($q_r \leq 1$) dominated by fluvial processes.

While Montgomery and Buffington posit a downstream trend of increasing fluvial control and decreasing influence of non-fluvial processes on channel morphology and dynamics at the watershed scale, Grant and Swanson (1995) attributed patchy patterns of riparian and channel disturbance to reach scale variations in the degree to which mainstem channels in mountain watersheds are constrained by hillslopes; bedrock outcrops; and valley floor landforms such as terraces, earthflows, and tributary alluvial fans. Where streams are narrow and constrained by adjacent landforms, channel gradients are higher than average and flows during floods are deep, leading to high shear stresses that promote erosion of the channel bed and banks and uprooting of riparian vegetation. Where the valley floor is wide and the stream is

laterally unconstrained, shear stresses are lower and deposition and lateral changes in channel position become the dominant form of channel disturbance (Grant and Swanson, 1995). Grant and Swanson (1995) concluded that the ratio of channel to valley flood width was the primary factor controlling where large floods scour and deposit sediment in mountain streams.

Because mountain streams often flow through forested landscapes and are both narrower and shallower than lowland rivers, large woody debris (LWD) plays a key role with respect to channel morphology and disturbance in many mountain streams. In small (1st to 3rd-order) channels, much of the available LWD is longer than the channel width and seldom if ever moves until it decays sufficiently to break into smaller pieces or is transported by a debris flow (Nakamura and Swanson, 1993). Wood typically comprises a major structural element in low-order stream channels, strongly influencing channel morphology (e.g., Keller and Swanson, 1979; Marston, 1982; Bilby, 1984; Nakamura and Swanson, 1993), and in some cases even controlling the distribution of alluvial vs. bedrock channel reaches (Montgomery et al., 1996). Smaller pieces that are close to or less than channel width in length interact the most strongly with sediment and have the greatest impact on channel structure and dynamics. In larger mainstem (4th to 5th-order) channels, LWD is relatively more mobile due to greater channel width and flow depth (Swanson and Lienkaemper, 1978; Lienkaemper and Swanson, 1987). LWD is less important as a structural element of the stream channel than in low-order tributaries, but perhaps more important as an agent of riparian vegetation disturbance. (Swanson et al., 1998; Johnson et al., in press). Large whole logs, or "key pieces" (Nakamura and Swanson, 1993) are most important in terms of their effect on channel form and the dynamics of channel and riparian disturbance.

Recent research into drainage basin and channel morphology and the processes which shape and disturb stream channels and valley floors in mountain watersheds have included many excellent theoretical and modeling studies (e.g., Wiberg and Smith; 1987; Furbish, 1993; Miller, 1995; Iverson, 1997), and laboratory flume experiments (e.g., Dietrich et al., 1989; Grant and Mizuyama, 1991; Braudrick et al., 1997). Field-based investigations have attempted to quantify long-term rates of

geomorphic processes (Dietrich and Dunne, 1978; Reneau and Dietrich, 1990); study rates, mechanisms, and interactions of processes from short-term observations (e.g., Dietrich and Smith, 1983; Dietrich et al., 1984; Wiberg and Smith, 1991; Whiting, 1997); or relate channel or valley floor characteristics to suites of gemorphic processes inferred to be responsible for their formation or modification using synoptic observations or measurements (e.g., Grant et al., 1990; Lisle and Madej, 1992; Montgomery and Dietrich, 1992; Grant and Swanson, 1995; Montgomery and Buffington, 1997).

Fewer published field studies have employed plot or transect-based repeated observations at relatively frequent intervals (i.e., seasonal to annual) over extended time periods (i.e., decades) to look at the dynamics of channel or landform change at annual to decadal time scales. This is not surprising, given that generating such long-term data sets requires considerable institutional investment and commitment over an extended period. One place where such studies have been done is Redwood Creek, California. Since the mid 1950s, annual cross section surveys at 58 locations distributed along the entire length of the creek and periodic longitudinal profile surveys have been used to monitor channel response to massively increased sediment yields resulting from timber harvest and associated road building effects in combination with several major floods in the mid 1950s through the mid 1970s (e.g., Nolan and Marron, 1995; Madej and Ozaki, 1996; Madej, in press).

This study draws on up to 50 years of streamflow data and 20 years of quasi-annual cross section monitoring data to explore the dynamics of channel response to peak flows on an approximately annual time scale at five $2^{nd}$ to $5^{th}$-order stream reaches arrayed within a $5^{th}$-order, 64 km$^2$ watershed in the Western Cascades of Oregon (Figure 3.1). This unique data set provides an opportunity to evaluate how the relationship between channel response and peak flow magnitude or frequency varies between streams of different order within a single watershed in which both the natural history and land management activities have been well documented. The overall goal of this research was to characterize the frequency, magnitude and spatial patterns of channel response to peak flows in the Lookout Creek watershed and to test hypotheses proposed in the fluvial geomorphology literature about controls on the response of

mountain stream channels to peak flow events. Specific objectives included the following:

1. Develop methods for characterizing channel response to floods at the channel unit to reach scale using historical cross section monitoring data.

2. Establish an empirical relationship between peak flow magnitude or recurrence interval and observed measures of cross section change.

3. Use the results of (1) and (2) to infer the frequency of peak flow events required to (a) initiate significant bedload transport or (b) substantially rework the channel bed at the cross section sites, and to assess whether between-site differences are consistent with expectations based on hypotheses proposed in recent geomorphologic literature.

4. Explore watershed scale spatial patterns in channel response to peak flows, with particular attention to differences between $2^{nd}$ to $3^{rd}$-order tributaries and $4^{th}$ to $5^{th}$-order mainstem streams.

5. Assess whether the relationship between flood magnitude and observed cross section response (objective 2 above) is affected by a major channel-restructuring flood such as the flood of February 1996—i.e., can a major flood alter the susceptibility of the channel to disturbance by subsequent floods?

# 8   Conceptual Approach

## 8.1   Spatial Variation in Geomorphic Processes with a Mountain Watershed

The Process Domains Concept (PDC; Montgomery, 1999) provides a useful framework for thinking about how dominant disturbance processes vary spatially within a mountain watershed and how this spatial variability governs both temporal patterns of channel and riparian disturbance and spatial patterns of habitat characteristics within the channel network. The basic premise of the PDC is that spatial variability in geomorphic processes controlled by topography, geology, and climate governs spatial and temporal patterns of physical and biotic disturbances that in turn influence ecosystem structure and dynamics. Figure 8.1 shows how physical disturbance processes and associated habitat characteristics are hypothesized by the PDC, as interpreted by the author, to vary spatially within the channel network in a typical Pacific Northwest mountain watershed, where debris slides and debris flows are important mass wasting processes.

Flood-related disturbance processes vary both with channel size or position within the drainage basin (Figure 8.1), and with flood magnitude (Figure 8.2). Disturbance of benthic and hyporheic habitat beneath the streambed begins when discharge increases sufficiently to initiate significant bedload transport within the channel thalweg. Substantial disturbance of riparian vegetation does not begin until flood stage increases sufficiently to begin to mobilize LWD (Figure 8.2), which then becomes a "tool" which greatly increases the effectiveness of floodwaters in battering and toppling riparian vegetation (Swanson et al., 1998; Johnson et al., in press). Truly major floods trigger widespread hillslope mass movements such as shallow debris slides and streamside slides, which can enter channels and cause "disturbance cascades" (Nakamura et al., in press) which propagate down the channel network. For example, a debris slide entering a low-order channel may become debris flow, which moves down the channel network and may enter a mainstem channel, where it may trigger a wood-rich flood surge. These disturbance cascades produce a gradient of

**Disturbance Processes**

Wind, fire

Landslides, earthflows

Debris flow initiation

Debris flow initiation and scour

Debris flow scour and deposition

Flooding

Channel scour and fill

Flooding (with & without wood movement)

Pulse wood + sediment inputs by debris flows

Channel scour and fill

Toppling/stripping of riparian trees

Same as confined mainstem channels, plus:

Lateral channel migration

Bank erosion

Channel avulsion

*Hillslopes*

*Hollows*

*Colluvial channels*

*Low order tributaries*

*Constrained mainstem channels*

*Unconstrained mainstem channels*

**Habitat Characteristics**

Infrequent, high-magnitude disturbance

Ephemeral discharge

Limited, stable (but intermittent) hyporheic zone

Dual-threshold bed mobility (frequent/infrequent)

Infrequent, high magnitude disturbance

Limited, stable hyporheic zone

Limited off-channel habitat

Moderately frequent bed mobility

Limited, stable hyporheic zone

Limited off-channel habitat

Moderately frequent riparian disturbance

Frequent bed mobility

Shifting channel position

Extensive, complex, changeable hyporheic zone

Complex off-channel habitat

Moderately frequent riparian disturbance

Figure 8.1. Schematic illustration of stream channel network showing characteristic disturbance processes and associated habitat characteristics for different portions of the channel network. (Modified from Montgomery [1999].)
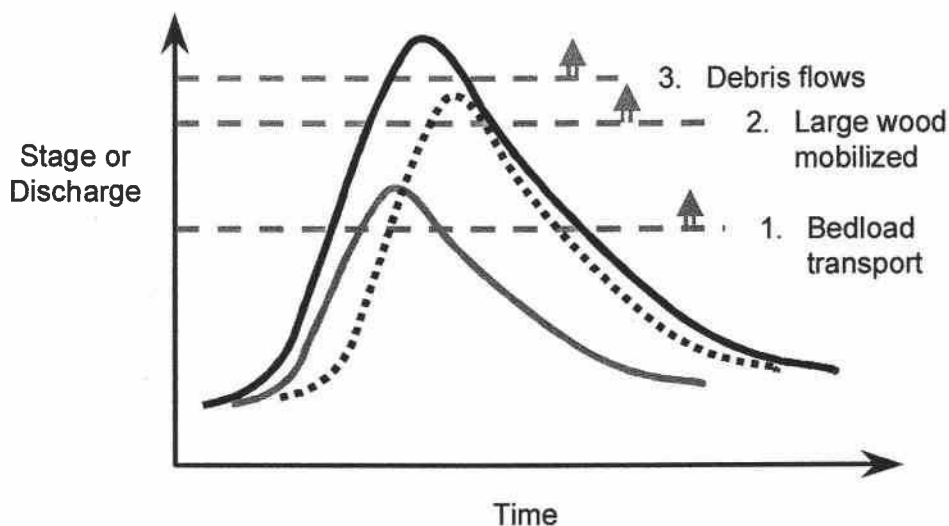
Figure 8.2. Disturbance processes as a function of flood magnitude. At moderately high discharge (1), bedload transport begins. During large floods (2), large wood is mobilized and can become a "tool" for battering riparian vegetation and banks. Major floods can trigger debris flows (3), causing direct scour and deposition in low order tributaries and providing large pulse inputs of wood and sediment to mainstem channels, greatly augmenting the potential geomorphic effectiveness of the flood.

stream and riparian disturbance of decreasing overall severity and increasing variability in severity in the downstream direction (Nakamura et al., in press).

Debris flows are a key process governing channel disturbance during major floods in both low-order tributaries and mainstem channels. Snyder (in preparation) found that debris flow related disturbances affected approximately 15% of the total channel network in the Lookout Creek watershed. In low-order tributaries, debris flows rework the channel through direct scour and deposition, primarily scour in 1st and 2nd-order channels and deposition in 3rd or higher order channels (Snyder, in preparation). Debris flows entering mainstem (4th-order or higher) channels can contribute large (1000s of m$^3$) volumes of wood and sediment, which can greatly magnify the geomorphic effectiveness of the flood in the receiving channel (Swanson et al., 1998; Wondzell and Swanson, 1999; Johnson et al., in press; Nakamura et al., in press).

The downstream variation in disturbance processes in Figure 8.1 reflects the gradual downstream decoupling of stream channels from adjacent hillslopes. At the tips of the channel network are bedrock hollows, which are small, unchanneled valley heads where thick sediment colluvial deposits gradually accumulate by soil creep, raveling and biogenic transport (e.g., roothrow and burrowing). Increasing soil thickness in combination with convergent patterns of surface and subsurface runoff in hollows leads to periodic evacuation of colluvial sediment by catastrophic debris slides with a natural recurrence interval on the order of thousands of years (Reneau and Dietrich, 1990, 1991). Immediately downslope of hollows are steep, ephemeral colluvial channels where the fluvial sediment transport is weak (Montgomery and Buffington, 1997). Here, scour by debris flows—typically to bedrock—is the dominant disturbance process, controlling channel incision and downstream transport of sediment (Benda, 1990; Seidl and Dietrich, 1992; Montgomery and Buffington, 1997) and wood (Benda and Sias, 1998) as well as riparian vegetation disturbance. The frequency of debris flows is much greater in 1st-order channels than in hollows due to numerous potential upslope source areas (Reneau and Dietrich, 1987). For a subset of the study area used in this investigation, Swanson et al. (1982a) estimated that debris flows in 1st-order channels draining small (~10 ha) watersheds have average recurrence interval of approximately 580 years.

Farther downstream, steep, low-order perennial tributaries whose channels are confined within narrow valleys may also be subject to relatively infrequent but severe disturbance by debris flows originating upstream. These channels—corresponding to cascade and step-pool channel types *sensu* Montgomery and Buffington (1997)—generally have a stepped longitudinal bed profile. Step-pool channels typically have two thresholds of bed mobility, with relatively frequent transport of finer (sand/gravel/cobble) bed material during moderate peak flows and infrequent transport of large step-forming or framework particles (Ashida et al., 1981; Grant et al., 1990; Schmidt and Ergenzinger, 1992; Montgomery and Buffington, 1997). They are transitional between debris-flow dominated colluvial channels and fluvially dominated mainstem channels.

Within the main valley bottoms, relatively low-gradient ($\leq$ 4% slope, roughly speaking) mainstem channels (corresponding to plane-bed, pool-riffle, or braided channel types in Montgomery and Buffington's [1997] classification system) are dominantly shaped by fluvial disturbance processes. Mainstem channels can be laterally constrained within bedrock gorges or by earthflows, tributary alluvial fans, terraces, or other valley-bottom landforms, or they may be unconstrained floodplain channels occupying wide valley bottoms (Grant and Swanson, 1995). In either case, bed mobility is predicted to be greater than in the steep tributary channels. However, Grant and Swanson (1995) report greater frequency of large boulders and greater channel roughness in constrained reaches, which may indicate greater channel stability relative to unconstrained reaches. Unconstrained mainstem channels are characterized by more extensive off-channel and hyporheic habitat than constrained channels and by greater lateral channel mobility (e.g., multiple channels, channel migration, channel avulsion), suggesting that they should be more dynamic than constrained reaches.

## 8.2    Cross Section Sampling Design

Long-term reference cross section monitoring sites were established at five locations in the Andrews Forest between 1978 and 1981 (Figure 3.1) and have been monitored at intervals of one to two years since establishment. The hierarchically nested sampling design of the cross sections (Figure 8.3)—five sites arrayed within a single watershed along a gradient of channel size ($2^{nd}$ to $5^{th}$- order channels) with multiple cross sections at each site arrayed along the channel at intervals of one to several channel widths—allows them to be used to assess channel changes over time at a range of spatial scales, ranging from the watershed scale (comparisons between sites) to the reach scale (individual cross section sites) to finer scales (sets of adjacent cross sections or changes within individual cross sections). In particular, they can be used to characterize channel response to floods across a range of flows (i.e., over the range of sizes of the largest peak flow between consecutive surveys) at each site (reach scale) and to compare these responses between sites located in different portions of the drainage network. The cross section data can thus be tested against

**Cross Section Scale**          **Watershed Scale**

**Reach Scale**
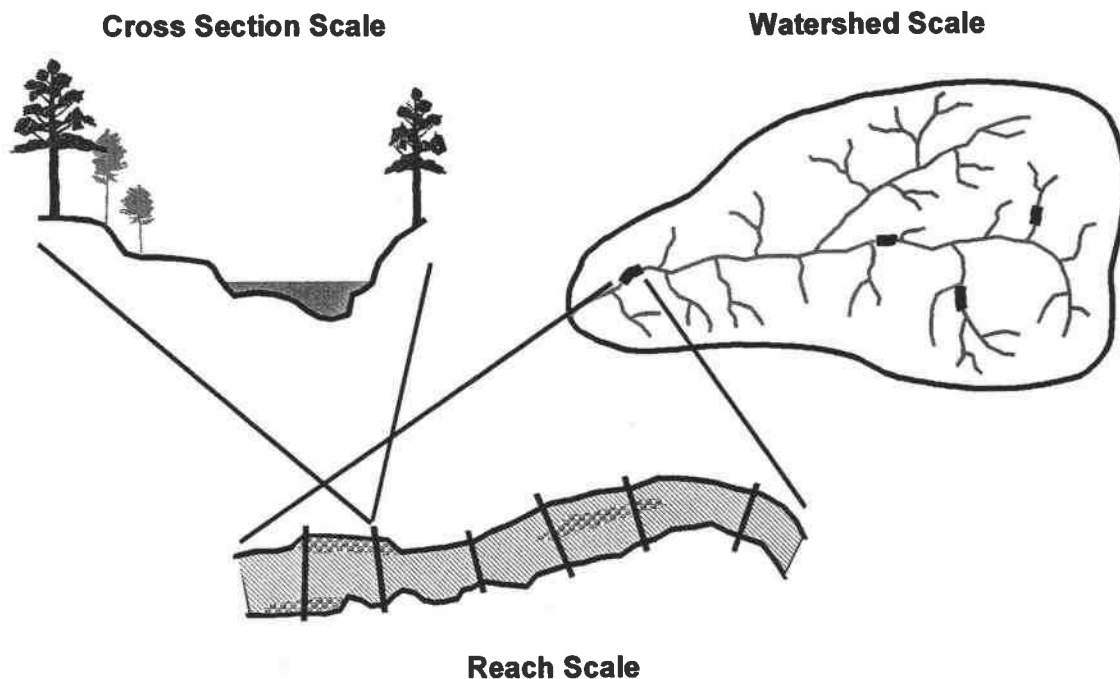
Figure 8.3. Schematic diagram showing nested cross section sampling design

predictions of the PDC and other hypotheses about watershed scale spatial patterns of channel dynamics, although the small number of sites and the lack of replication precludes any statistical hypothesis testing at this scale.

## 8.3 Styles of Channel Response Inferred from Cross Section Changes

A variety of different styles of channel adjustment can be inferred from changes in the cross section profiles (Figure 8.4). A lowering of all or a part of the streambed is classified as scour or degradation (Figure 8.4[a]), while an increase in the bed elevation within all or a portion of the channel due to deposition within the channel is classified as fill or aggradation (Figure 8.4[b])[1]. A combination of both significant scour and fill within a single cross section (Figure 8.4[c]) is a common response that may reflect complex channel adjustments, such local scour and fill

[1] The terms aggradation and degradation are typically reserved for changes that affect the entire bed of at least the perennially wetted portion of the channel (i.e., the low flow channel), and are used in that sense here.
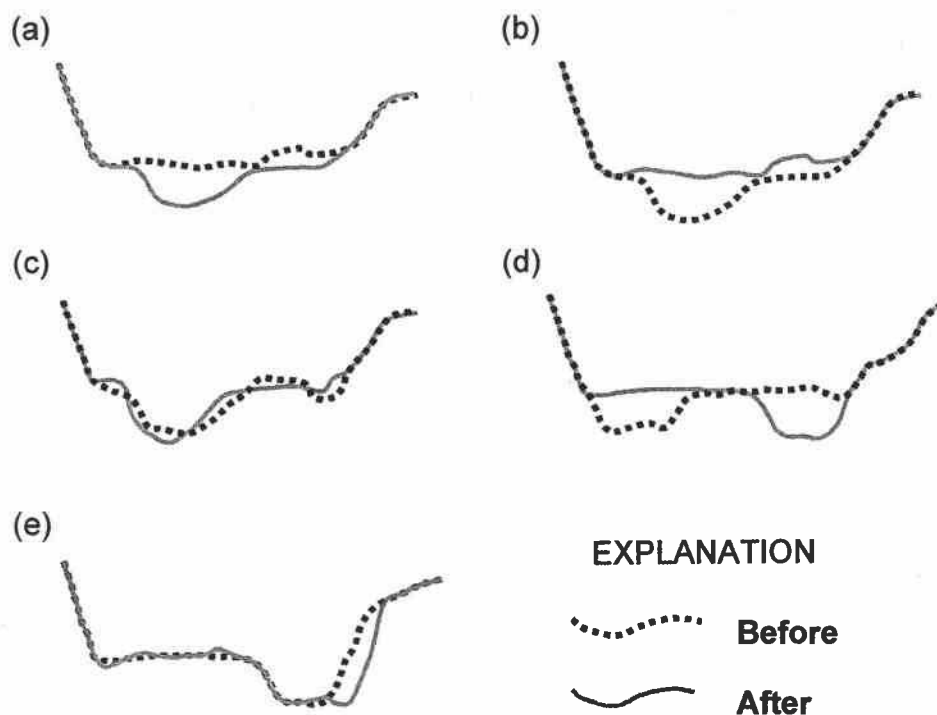
Figure 8.4. Styles of channel response inferred from hypothetical cross section profile changes: (a) degradation or scour, (b) aggradation or fill, (c) mixed scour and fill, (d) lateral channel shift, and (e) bank erosion.

around a large log or deepening of the channel thalweg accompanied by deposition on or lateral accretion of an adjacent lateral bar. A lateral channel shift (Figure 8.4[d]) also typically involves both scour and fill within a single cross section, but is distinguished by the creation of a new low flow channel with or without filling in of the previous channel thalweg. Bank erosion is distinguished by a lateral retreat of the bank (Figure 8.4[e]), but excludes lateral channel erosion within the floodway. For the purposes of this study, the bank, or edge of the active channel floodway, was distinguished on the basis of topography and a transition from a recent alluvial substrate (e.g., cobble, gravel, etc.), indicating periodic disturbance by high energy flood flows, to a soil-covered surface with terrestrial vegetation.

### 8.4 Conceptual Model for Reach Scale Channel Response

In a generic sense, the response of a stream channel to a flood or peak flow event at the reach scale can be quantified in at least three ways: (1) as the probability of observing a measurable response exceeding some threshold criterion at a particular point in space, (2) as the proportion of the stream channel length or area reworked or altered over a specified reach, or (3) as some measure of the magnitude of response, such as volume of sediment per unit stream length reworked (scoured and/or deposited). The first two measures are equivalent if the probability of response is independent of location, since if a particular flood reworks $x$ percent of the stream channel in a randomly distributed fashion, then the probability of observing a change at a randomly chosen point within the stream channel is also $x$ percent. Thus, we have two types of measures of channel response: probability of response and magnitude of response. The core historical data set used in this study, repeated surveys of sets of 11 to 20 cross sections at fixed locations within five reference reaches, can be used for either type of measurement, and both types were used in this study.

Figure 8.5 presents several hypothetical channel "response curves," in which the measure of channel response (plotted on the y axis) is the probability of observing change that exceeds some response criterion (e.g., a detection limit or an arbitrarily specified value) at a randomly selected cross section location (or, equivalently, the proportion of cross sections within a reach that exhibit such changes). The independent variable driving the response (plotted on the x axis) is a measure of flood magnitude, such as the maximum instantaneous peak unit area discharge, $Q^{*}$,[2] for the time period between successive observations (i.e., cross section surveys). Thus, the response curve specifies, for any value $Q^{*}_{p}$ of $Q^{*}$, the probability $p$ that some measure of channel change, $\Delta$, exceeds a detection limit or other specified value, $\delta_{0}$. We can write this mathematically as

$$p = \Pr\{\Delta \geq \delta_{0} \mid Q^{*} = Q^{*}_{p}\} \qquad (8.1)$$

---

[2] Unit area discharge is the discharge at a point divided by upstream drainage area, which is an appropriate measure for peak flows that are to be compared across a range of stream sizes. Alternatively, the independent variable driving the response could be some measure of applied stress derived from the peak flood discharge, such as peak average boundary shear stress acting on the bed.
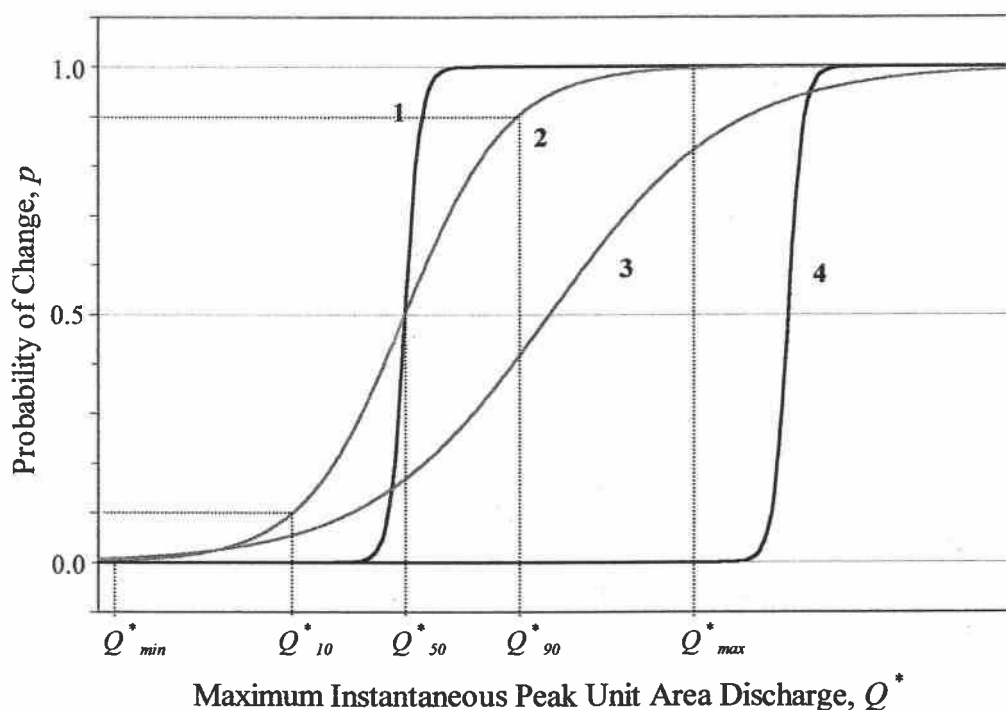
Figure 8.5. Hypothetical channel response curves showing probability of observing a change in channel cross sectional profile as a function of increasing maximum peak instantaneous discharge for the period between consecutive observations. Labeled values of $Q^*$ ($Q^*_{min}$, etc.) refer to curve 2. $Q^*_{min}$ represents the value of $Q^*$ below which there is a neglible chance of observing change, while $Q^*_{max}$ represents the value of $Q^*$ above which channel change is essentially certain. $Q^*_{xx}$ denotes the value of $Q^*$ associated with an $xx$ percent probability of observing channel change at a randomly selected location in the hypothetical stream reach represented by curve 2.

where the change measure, $\Delta$, is treated as a random variable that is some unknown function of $Q^*$.
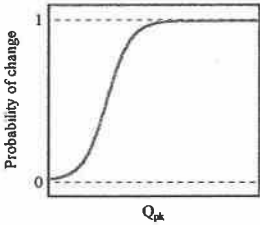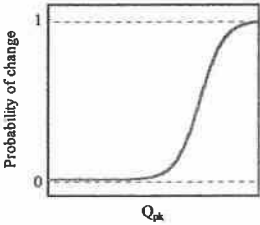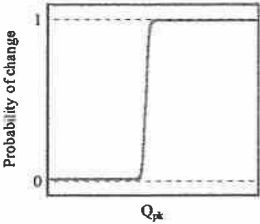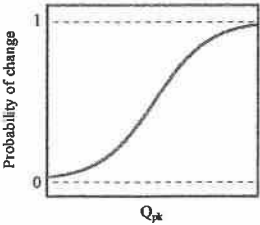
Let us assume that the probability of observing a response will be essentially zero for very low values of $Q^*$ and essentially one for very high values of $Q^*$. That is, we assume that there is some lower limit on discharge below which detectable channel changes never occur and some upper limit above which detectable changes always occur. These limits—call them $Q^*_{min}$ and $Q^*_{max}$, respectively (see Figure 8.5)— bracket the rising limb of the response curve, which is the part that characterizes the nature of the channel response. In comparing the response of two stream reaches, two

characteristics of the response curve that are of particular interest are the slope and position along the x axis of this rising limb. The slope determines how gradually or abruptly the probability of channel adjustment increases with increasing discharge above $Q^*_{min}$. If the slope is low ($Q^*_{max} >> Q^*_{min}$), the increase in response probability is gradual and may be approximately linear over a fairly wide range of discharge (e.g., curve 3 in Figure 8.5). At the opposite extreme, if the slope of the rising limb of the response curve is very steep, the response curve can become almost a step function (Figure 8.5, curves 1 and 4), indicating a threshold-type response in which a small incremental increase in $Q^*$ is associated with a very large increase in the probability of a response being observed. Since the response probability $p$ may never actually equal zero or one but only asymptotically approach these values, it may be more useful in practice to replace $Q^*_{min}$ and $Q^*_{max}$ with values of $Q^*$ corresponding to specified probabilities values of $p$—say, 10% and 90%, or $Q^*_{10}$ and $Q^*_{90}$, respectively (Figure 8.5).

The lateral position along the x axis of the rising limb of the response curve characterizes the relative resistance of the channel to disturbance. A logical choice as a measure of this property for comparing channels whose response curves may have different slopes (e.g., curves 1 and 2 or 3 and 4 in Figure 8.5) is the value of $Q^*$ corresponding to a 50% probability of change (i.e., the midpoint of the rising limb), or $Q^*_{50}$ (Figure 8.5). However, it may also be instructive to compare the values of $Q^*$ for different reaches corresponding to other specified response probabilities. For example, $Q^*_{10}$ may be thought of as representing the peak flow magnitude at which mobilization of the bed begins to occur, while $Q^*_{90}$ may be interpreted as the minimum peak flow magnitude required for widespread reworking of the channel bed.

Within this framework, the response of a channel may be characterized as either threshold-like or gradual and as exhibiting either a low or high resistance to disturbance (Figure 8.5). Two reaches may both exhibit clearly defined thresholds but at different values of $Q^*_{50}$ (Figure 8.5, curves 1 and 4), or they may exhibit the same overall resistance to disturbance (same $Q^*_{50}$) but differ in the degree to which they express threshold-like or gradual response behavior (e.g., Figure 8.5, curves 1 and 2).

Table 8.1. Relationship between channel attributes at the cross section to reach scale and expected channel response characteristics

| Channel Response Characteristic | Cross Section/Reach Attributes | Response Curve |
|---|---|---|
| Low resistance to disturbance | - fine particle size<br>- few large roughness elements[1]<br>- low bedform resistance<br>- plane-bed or pool-riffle channel type[2] |  |
| High resistance to disturbance | - coarse particle size<br>- bedrock or resistant bed/banks<br>- abundant large roughness elements[1]<br>- high bedform resistance<br>- cascade or step-pool channel type[2] |  |
| Well defined response "equal mobility" | - homgeneous particle size distribution<br>- few large roughness elements[1]<br>- relatively uniform channel width<br>- relatively uniform channel gradient |  |
| Poorly defined response 'selective transport' | - patchy particle size variations<br>- abundant large roughness elements[1]<br>- locally variable channel width<br>- locally variable channel gradient |  |

Notes:

[1] very large boulders, large logs, etc.

[2] per channel classification scheme of Montgomery and Buffington (1997)

Alternatively, the response of the reaches may differ in both respects, as is the case for curves 3 and 4 in Figure 8.5.

Table 8.1 presents a conceptual model of channel response to peak flows based on these channel response characteristics—i.e., low vs. high resistance to disturbance and abrupt (threshold-like) vs. gradual response to increasing peak flow magnitude. For each response characteristic in column 1, column 2 lists channel attributes at the scale of the reach to the individual cross section that are hypothesized to give rise to that response behavior. The third column in Table 8.1 shows a sample response curve of the type that would be expected for a channel with the indicated attributes.

Certain channel characteristics are expected to contribute to low or high resistance to disturbance by peak flows. Low resistance to disturbance is hypothesized to be associated with relatively finer particle size, few large roughness elements such as very large boulders or logs, and low bedform resistance—in other words, with low hydraulic roughness (Table 8.1). Channel types characteristic of "response" segments in the Montgomery and Buffington (1997) classification scheme (i.e., plane-bed, pool-riffle, and dune-ripple channels) would be expected to have these attributes and, hence, to exhibit relatively low resistance to disturbance. At the channel unit scale, pools would be expected to exhibit more frequent changes than other channel unit types (i.e., riffles, rapids, cascades, or steps), since they are characterized by generally finer particle size and lower relative roughness (Grant et al., 1990), and since pools may act as temporary storage sites for finer bed material than that which comprises the channel bed generally (Lisle and Madej, 1992).

On the other hand, high resistance to disturbance is expected for channels having bedrock or other resistant bed/bank material and/or high hydraulic roughness characterized by relatively coarser particle size, abundant large roughness elements, and/or high bedform resistance (Table 8.1). Channel types characteristic of "transport" segments (i.e., bedrock, cascade, or step-pool channels; Montgomery and Buffington, 1997) tend to have these attributes and hence would be expected to exhibit relatively high resistance to disturbance.

Certain channel characteristics also are expected to promote either a well-defined threshold of channel response or, alternately, a more gradual increase in the

degree of channel response with increasing discharge. A well-defined response threshold might be expected to be associated with a relatively homogeneous channel characterized by a narrow range of particle sizes comprising the bed, few large roughness elements, and relatively uniform channel width and gradient (Table 8.1). However, some field and laboratory based studies have suggested that even in a bed of mixed particle sizes, particles of all sizes may be entrained over a narrow range of flow conditions due to the greater exposure of larger particles that protrude from the bed, "hiding" of smaller particle by larger ones, or the development of a surface pavement of relatively uniform size that regulates the transport of finer, more heterogeneous bed material (Parker et al., 1982; Andrews, 1983; Wilcock and Southard, 1988). This "equal mobility" hypothesis is consistent with a threshold type channel response.

In contrast, a poorly defined response threshold is hypothesized to be associated with relatively heterogeneous bed material particle size, abundant large roughness elements, and local variations in channel width and gradient. Heterogeneous particle size should lead to a more gradual reach scale channel response with a poorly defined response threshold (bottom row in Table 8.1) under certain conditions. These include selective transport of different particle sizes (e.g., Komar, 1987; Shih and Komar, 1990a, 1990b), which may be enhanced by spatial variability in local hydraulic conditions and sediment mobility resulting from heterogeneity at scales larger than the individual particle (e.g., sediment patches, bedforms, large logs, variations in channel width, etc.).

## 8.5   Study Design

This study used a combination of historical monitoring data, additional field work to characterize the long-term cross section references sites, and a variety of analytical approaches in pursuit of the research objectives set forth in Chapter 1. Major components of the study included the following:

1.  Study site characterization,
2.  Peak flow analysis,

3.  Statistical analysis of observed probabilities of channel cross section response probability in relation to peak flow magnitude, and

4.  Descriptive analysis of channel and riparian response to two large floods, with an emphasis on differences between tributary and mainstem streams.

First, study site characterization field work was undertaken to map the position of the cross sections relative to each other and to channel features, and to provide a geomorphic context for each site. Second, an analysis of historical peak flow data from stream gaging stations within the study area was performed to characterize the magnitude, frequency and recurrence intervals for the peak flow events driving the channel responses observed at the reference cross sections. In the third component of the study, logistic regression was used in conjunction with a classification-based analysis of the cross section data to assess the relationship between peak flow magnitude or recurrence interval and the proportion of cross sections at a site exhibiting a detectable response. These results were used to infer the frequency of specified levels of relative channel disturbance at four of the cross section sites. The fourth component of the study inferred differences between low-order tributary sites and mainstem sites in the style and degree of disturbance caused by a moderately large flood (6- to 12-year recurrence interval) in 1986 and a major flood (25 to 100+ year recurrence interval) in 1996 using quantitative measures of the magnitude of channel response at the cross section sites as well as qualitative observations of flood effects.

# 9 Study Area and Methods

This chapter describes the study area and the field and analytical methods employed in this study. Section 9.1 describes the study area and the physical characteristics and geomorphic setting of the cross section sites. Section 9.2 describes the historical data sets used and issues pertaining to data collection methods for the cross section data set in particular. Methods employed by the author in conducting supplemental field investigations at the cross section study sites are described in Section 9.3. Section 9.4 details how the historical cross section data were prepared for analysis, including error checking and quality control measures and corrections and adjustments applied to the data. Data preparation for mapping and surveying is described in Section 9.5. Finally, methods used to analyze peak flow data and cross section changes are presented in Sections 9.6 and 9.7, respectively.

## 9.1 Study Area

### 9.1.1 H.J. ANDREWS EXPERIMENTAL FOREST

The H. J. Andrews Experimental Forest (Andrews Forest) occupies the $5^{th}$-order, 64 km$^2$ watershed of Lookout Creek located, at the eastern edge of the Western Cascades in the Willamette National Forest, Oregon (Figure 3.1). The elevation range in the watershed is 410 to 1630 m. Approximately three-quarters of the watershed is forested with 100- to 500-year old stands dominated by Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*) and by western redcedar (*Thuja plicata*) at lower elevations and by Pacific silver fir (*Abies amabilis*) at upper elevations. Approximately 20% of the watershed was harvested from 1950 to 1970, and a further 5% was harvested by 1990 (Jones and Grant, 1996). Annual precipitation ranges from approximately 2300 to 3500 mm, depending on elevation, over 80% of which falls from November through April. Rain-on-snow events in the "transient snow zone" between 400 and 1200 m are a major factor in generating most

large floods in the Andrews (Harr, 1981; 1986), including the December 1964 and February 1996 floods, the largest on record in the watershed.

Glacial, fluvial, and mass movement processes have all played important roles in shaping the current landscape of the Andrews Forest (Swanson and James, 1975a, 1975b). The Forest is underlain by bedrock consisting principally of volcaniclastic rocks and lava flows of late Oligocene to Pliocene age, intruded in the lower part of the basin by northwest to southeast-trending dikes (Peck et al., 1964; Swanson and James, 1975a; Priest et al., 1983). The volcaniclastic rocks tend to be deeply weathered, and the landscape is deeply dissected. Glacial deposits are found in the upper part of the Lookout Creek watershed, extending down to at least 1 km downstream of the Mack Creek confluence (Figure 3.1) and to the 2,500-foot (760 m) elevation along McCrae Creek (Swanson and James, 1975a). A fluvial terrace 5 to 8 m above the present channel occurs along the lower 4 km of Lookout Creek; this terrace was abandoned at least 7,000 years ago based on the presence of deposits Mazama ash on its upper surface. The current channel is incised into the terrace and into inactive alluvial fans (also pre-Mazama ash) deposited on the terrace and lower floodplain survaces (Swanson and James, 1975a, 1975b). A wide segment of valley floor (300 to 400 m across), underlain by alluvial sediments, extends from a point 5 km upstream of the mouth of Lookout Creek to about 1 km downstream of the Mack Creek confluence, a distance of about 4.5 km (Figure 3.1). This feature is the result of deposition before mid-Holocene time upstream of a channel constriction caused by a massive, now inactive, earthflow (Swanson and James, 1975a).

Both slow, deep-seated earthflows and rapid, shallow mass movements (debris slides and debris flows) are important processes within the Andrews Forest. Both types of mass movements occur predominantly in areas underlain by deeply weathered volcaniclastic rocks, particularly where these are overlain by more resistant lava flows (Swanson and James, 1975a). A majority of the documented debris flows within the Andrews Forest during the past 50 years (Figure 9.1) have been observed at elevations of between 600 and 800 m, where this transition from weak to resistant bedrock occurs (Dyrness, 1967; Swanson and James, 1975b; Snyder, in preparation).
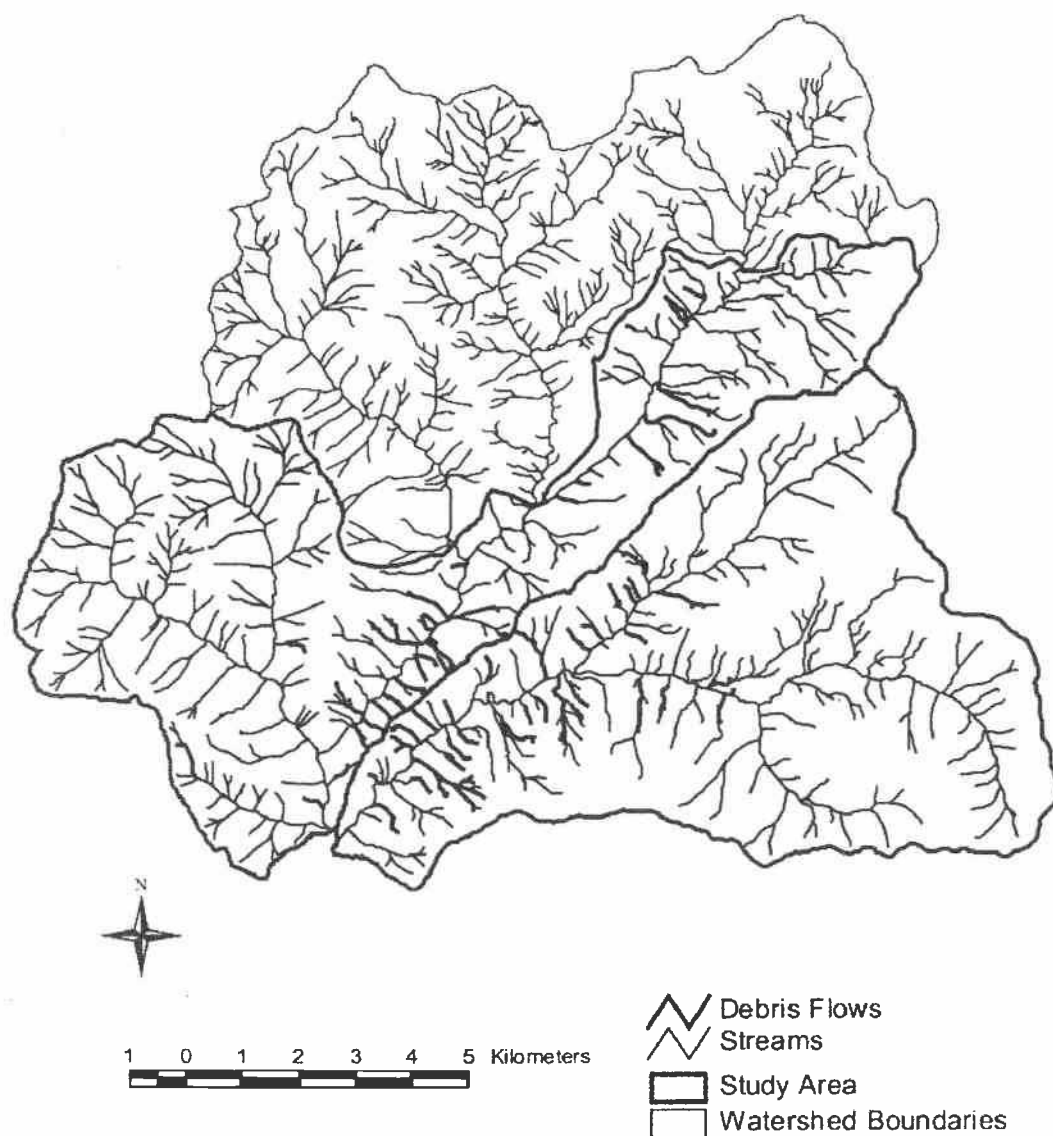
Figure 9.1. Locations of known debris flows in the Lookout Creek watershed and a portion of the Upper Blue River watershed, 1946-1996. (Source: Snyder, in preparation)

Table 9.1. Cross section site characteristics.

| Site | | COC | MAC | MCC | LOM | LOL |
|---|---|---|---|---|---|---|
| No. of cross sections | | 17 | 12 | 20 | 11 | 14 |
| Drainage area, $km^2$ | | 0.71 | 5.6 | 5.9 | 31.7 | 61.5 |
| Elevation at lower end, m above msl | | ~ 1000 | 766 | 734 | ~ 575 | ~ 435 |
| Avg. channel slope | | 0.168 | 0.100 | 0.096 | 0.032 | 0.015 |
| Avg. channel width, m | | 5.3 | 13.0 | 10.7 | 24.7 | 27.3 |
| Reach length, m | | 170 | 230 | 230 | 300 | 470 |
| Reach length: avg. channel width | | 32.1 | 17.7 | 21.5 | 12.1 | 17.2 |
| Bed surface particle size | $D_{84}$ | 301 | 302 | 230 | 305 | 234 |
| in mm (1995 data) | $D_{50}$ | 95 | 77 | 57 | 147 | 100 |
| | $D_{16}$ | 20 | 17 | 14 | 38 | 30 |
| Degree of channel constraint | | high | high | high-mod. | low | high-mod. |
| Adjacent forest type[1] | | old-growth | old-growth | young conifer | old-growth, mixed | old-growth, young |
| Abundance of in-channel CWD | | high | high | low | mod. | low |

[1] old-growth = conifers > 200 yr; young conifer = conifers < 40 yr (plantation); mixed = mature mixed conifer & hardwood forest

The following sections describe the general characteristics and geomorphic setting of the individual cross section sites. The five cross section sites (reaches) can be viewed as being arrayed along a hydrologic and geomorphic gradient from the headwaters (Cold Creek site) to the mouth (lower Lookout Creek site) of the Lookout Creek watershed. Along this gradient, drainage area and channel width systematically increase, while channel slope systematically decreases. Other characteristics—such as the abundance of LWD and the degree to which the channel is constrained laterally by valley walls, terraces, or other non-fluvial or relict landforms—vary in a less systematic fashion (Table 9.1).

### 9.1.2  COLD CREEK

The Cold Creek (COC) site is a high elevation (1000 m) headwaters channel with a drainage area of approximately 71 ha (0.71 km$^2$; Table 9.1). While Cold Creek likely experienced some degree of past glaciation, the study reach is narrow (5.3-m average channel width), highly constrained by valley sidewalls, and quite steep (average gradient of 17%). The channel contains abundant woody debris (Figure 9.2), but most of the larger pieces and the majority of the volume of LWD is suspended well above the channel bed. The longitudinal profile of the channel has a decidedly stepped appearance, with most of the fall occurring as boulder or log steps. The channel would be classified as a cascade channel type in the Montgomery and Buffington (1997) classification scheme.

The reference reach contains 17 cross sections, labeled XS 1 to XS 17, with numbers increasing upstream (Figure 9.3). The lowermost cross section is located approximately 50 m upstream of Forest Road 1506, the main access road into the Andrews Forest, and the uppermost cross section is located approximately 170 m farther upstream.

The channel contains many large boulders and logs (Figures 9.2 and Appendix C, Figures C.1 through C.6) which appear to be immobile under the current hydrologic regime, at least with respect to purely fluvial transport processes. Even small boulders and larger cobbles are typically moss-covered, indicating lack of recent transport.

Figure 9.2. View of channel at the Cold Creek (COC) cross section site.

However, pools and other low-gradient channel units between longitudinal steps contain a substantial amount of gravel- to cobble-sized sediment (as well as minor sand) which appears to be actively transported.

While the canyon drained by Cold Creek is narrow, its floor and lower sidewalls exhibit a distinctly trough-shaped cross-section, which may be the result of repeated scour by debris flows. Within this U-shaped trough are small (several $m^2$ to several tens of $m^2$), low (0.25-0.5 m above the low flow water surface) floodplain-like surfaces adjacent to the channel, which in at least some instances appear to have been formed by slumping of the valley sidewalls. Vegetation on these surfaces showed no sign of disturbance following the major flood of February 1996. The absence of large trees adjacent to the channel within the U-shaped trough (despite the lack of evidence of any recent disturbance) suggests that the channel may have experienced debris flows within recent decades. However, debris flow surveys conducted in the Andrews Forest in the 1960s, 1970s and 1990s show no evidence of debris slides or debris
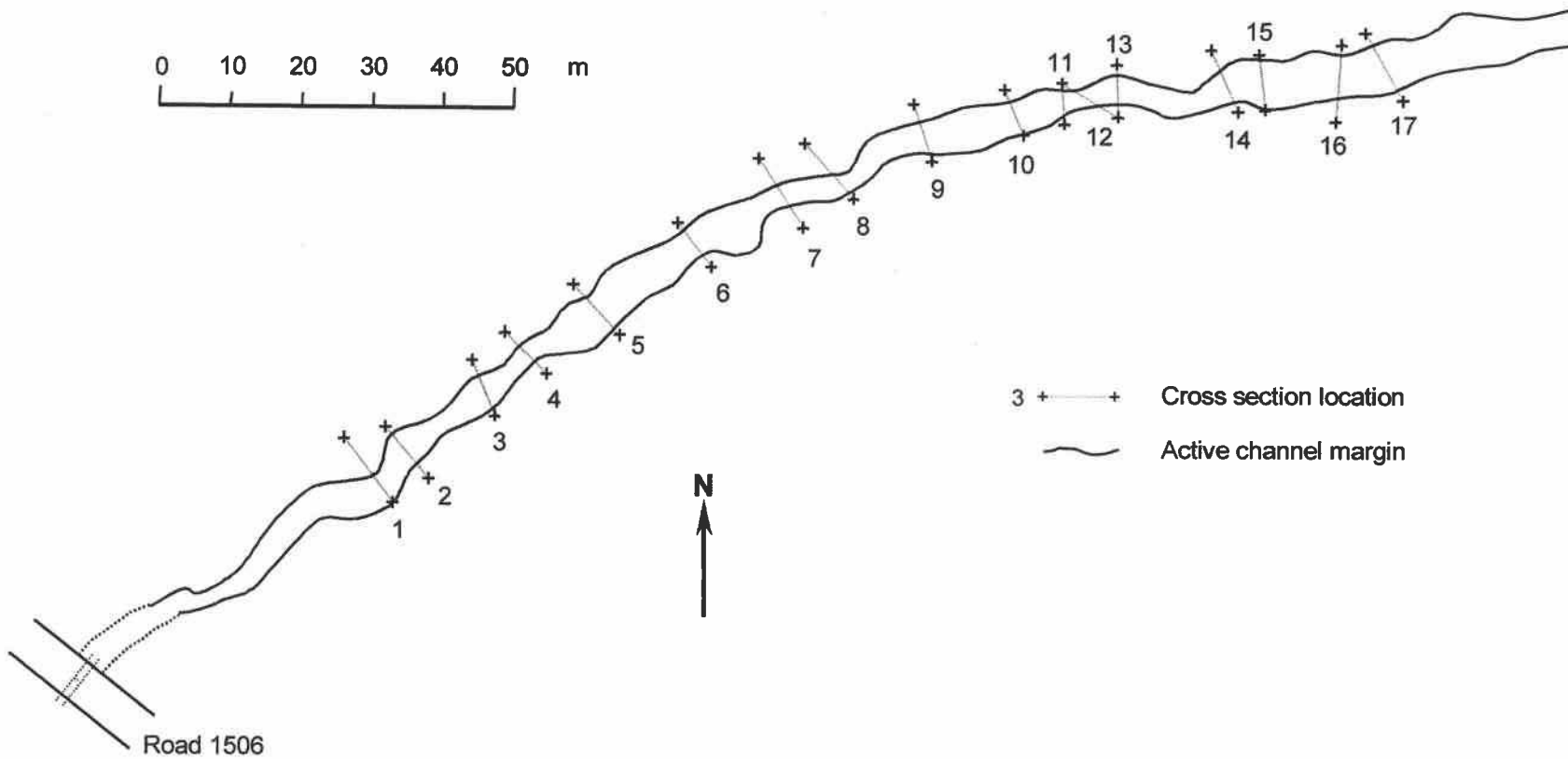
Figure 9.3. Map of Cold Creek (COC) site showing cross section locations.

flows in this part of the watershed and none originating above an elevation of approximately 3500 ft (1070 m); most have occurred between elevations of 2000 and 2600 ft (600 to 800 m) (Dyrness, 1967; Swanson and James, 1975b; Snyder, in preparation).

Cold Creek is the only 2$^{nd}$-order tributary in which long-term cross section monitoring has been conducted, but it is quite different from the better studied, low elevation small watersheds of similar size (WS 1, 2 and 3, Figure 3.1), which have produced documented debris slides and debris flows. The latter streams are probably more representative of "typical" low-order streams in the western Cascades, particularly those located in areas affected by timber harvest.

### 9.1.3  MACK CREEK OLD-GROWTH AND CLEARCUT SITES

The Mack Creek old-growth (MAC) and clearcut (MCC) sites are nearly adjacent, contrasting 320-m long reaches at the downstream end of the undisturbed portion of the Mack Creek watershed (Figure 3.1). The MAC reach flows through old-growth forest in which Douglas fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and western redcedar (*Thuja plicata*) form a nearly closed canopy over the stream channel. Bigleaf maple (*Acer macrophyllum*) also grow within the riparian zone. Woody debris is abundant within the channel, including many logs greater than 75 cm in diameter and a few as large as 1.5 m in diameter (Figure 4.3). Unlike Cold Creek, a majority of these logs rest on or partially on the channel bed rather than being suspended above the channel, due to the wider channel and valley floor. Many of the pieces less than 10 m in length have been fluvially transported at least some distance, and much of the LWD is concentrated into accumulations which span part or all of the channel (Figure 4.3). Within the MAC reach, there are two log steps and one large channel-spanning LWD accumulation (LWD jam); a second large LWD jam occurs just upstream of the uppermost MAC cross section (XS 12; Figure 9.4).

In contrast, the slopes adjacent to the channel at the MCC site were clearcut in 1964-65, and the reach contains very little woody debris and essentially no large logs
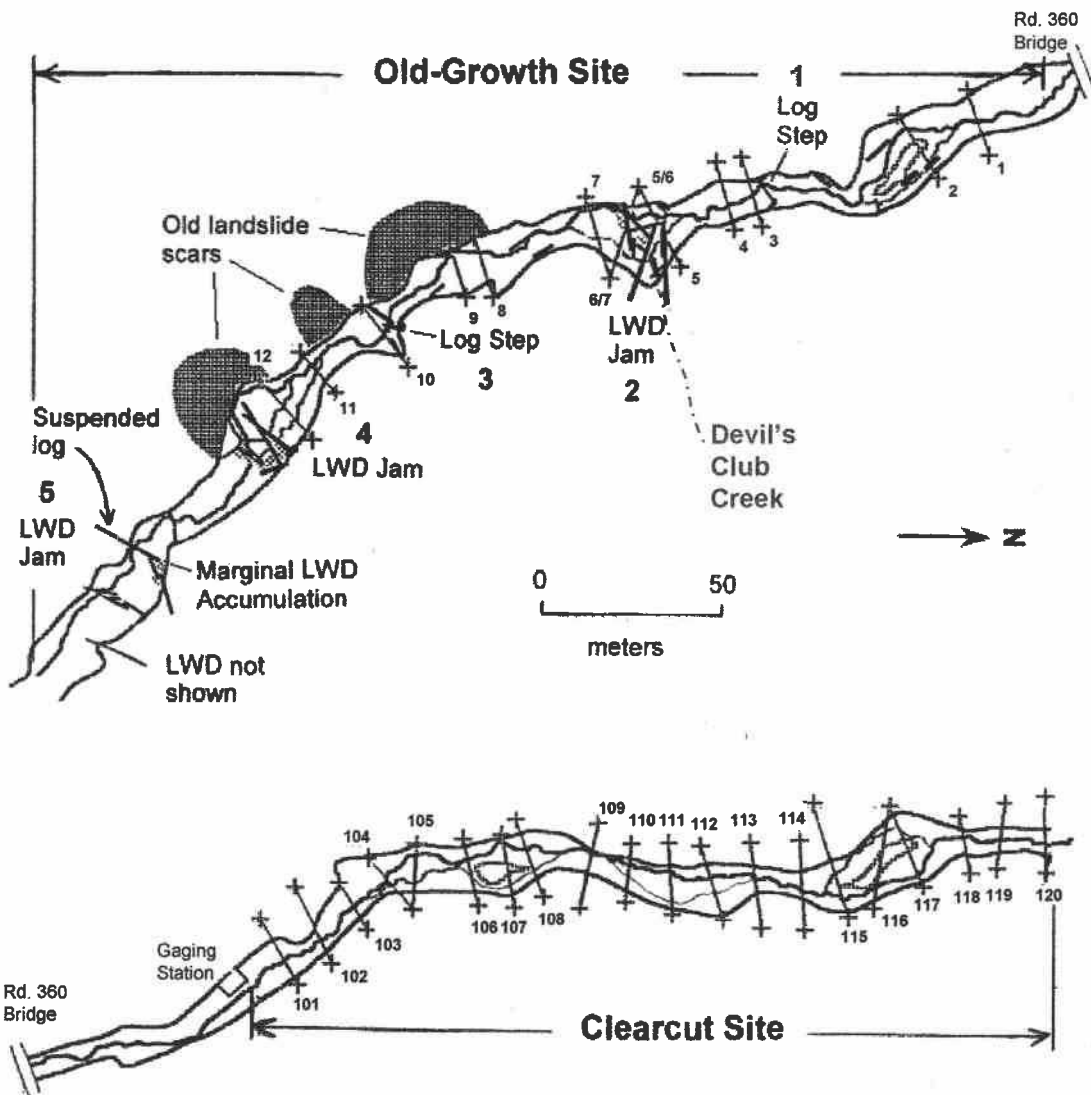
Figure 9.4. Map showing selected channel features and cross section locations at the Mack Creek old-growth (MAC) site, top, and the clearcut (MCC) site, bottom. Downstream is toward the right.
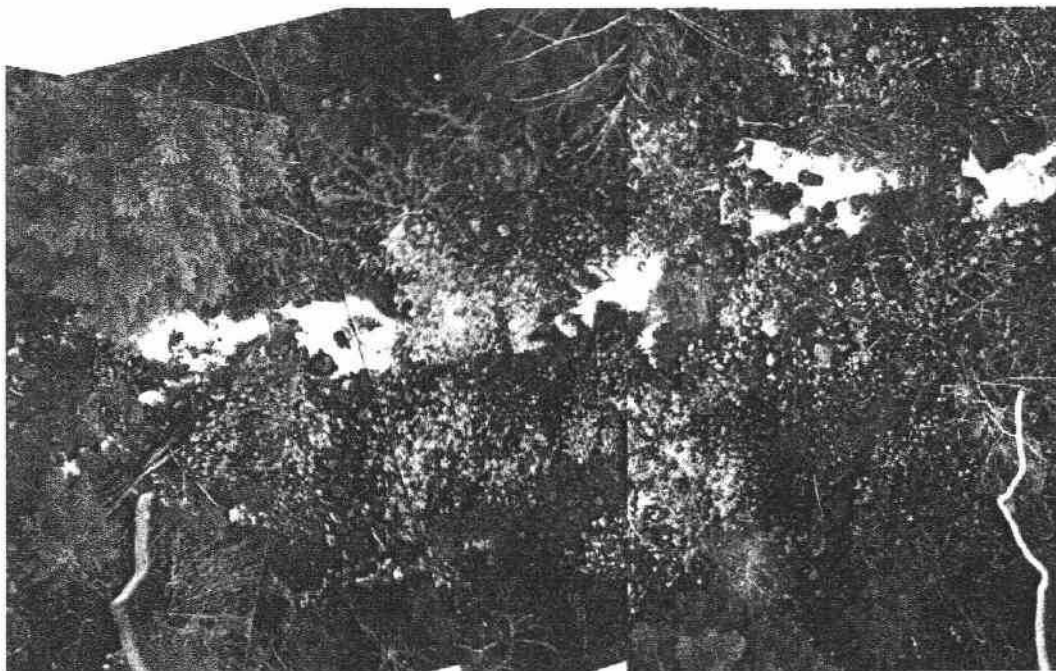
Figure 9.5. Aerial view of a portion of the Mack Creek clearcut (MCC) reach. Note steep, step-pool configuration of main channel. Side channel at bottom of photo, separated from main channel by a willow-covered bar, is active at this moderate fall flow.

(Figure 9.5). LWD was removed from the channel during the logging operation and by a major flood in December 1964, and regrowth on the streambanks and adjacent hillslopes is not yet capable of supplying much LWD to the channel. Inputs of LWD from the upstream reach (particularly large pieces) were effectively blocked by a culvert at the road crossing at the downstream end of the old-growth site prior to removal of the culvert and its replacement by a bridge in September 1994.

The old-growth reach contains 12 cross sections which are numbered XS 1 through XS 12 in the upstream direction; the lowermost (XS 1) is located approximately 30 m upstream from the bridge (Figure 9.4). The clearcut reference reach contains 20 cross sections, assigned 3-digit numbers (XS 101 through XS 120) that, contrary to the old-growth reach, increase in the *downstream* direction (Figure 9.4). The uppermost MCC cross section is located approximately 75 m downstream of the road crossing.

The Mack Creek gaging station (Figure 9.4) is located at the upstream end of the clearcut reach. The gaging station flume creates an abrupt drop of over 2 m—in essence, an artificial waterfall—less than 15 m upstream of XS 101 (Figure 9.4). The elevation and drainage area for this station are 758 m and 5.81 ha (5.81 km$^2$), respectively. Drainage areas at the downstream ends of the old-growth and clearcut reaches, estimated from 30-m DEM, are 5.6 and 5.9 km$^2$, respectively (Table 9.1). Average channel width is approximately 13 m for the old-growth reach and approximately 11 m for the clearcut reach, but the width is quite variable in both reaches. Average channel gradient was estimated from the longitudinal profile survey to be 10.0% for the old-growth reach and 9.6% for the clearcut reach.

The old-growth reach is fairly tightly constrained by adjacent hillslopes, particularly along the left bank, where there are several landslide scars in which large trees are absent and bedrock is exposed (Figure 9.4). The right bank is generally less steep and lacking in bedrock. Much of the right bank is bordered by a high, terrace-like landform, possibly residual glacial deposits. A 1$^{st}$-order tributary informally named Devil's Club Creek enters from the right between XS 5 and 6. The tributary is incised into antecedent alluvial fan deposits. Bedrock is also exposed sporadically in the channel bed and banks within the old-growth reach, particularly where flow is directed against the bank as in the vicinity of XS 12 and XS 8 and 9 on the left bank (all of which are located at the foot of landslide scars, Figure 9.4) and at the sharp left bend in the channel between XS 2 and 3. However, most of the bed within the old-growth reach is covered with alluvial sediment, even in areas with bedrock banks.

However, extensive areas of bedrock are exposed in the channel bed between the bridge and the upper end of the clearcut reach, especially within a narrow (7-m wide) boulder-armored section extending about 25 m downstream from the bridge. This boulder-armored channel was constructed in the summer of 1994, when the 10 ft (3 m) diameter, 75 ft (23 m) long culvert pipe previously at the road crossing was removed to improve fish passage. Approximately 1200-1500 yd$^3$ of sediment were excavated at that time (Cissel, personal communication). Bedrock is also exposed in the channel bed within the two uppermost MCC cross sections (XS 101 and 102), but was not present at this location prior to the 1996 flood. No bedrock is exposed within

the bed or banks of the clearcut reach downstream of XS 102, nor was any observed between the downstream end of the clearcut reach and the confluence of Mack Creek with Lookout Creek—a distance of approximately 700 m—during a reconnaissance trip in the summer of 1997.

The clearcut reach is somewhat less tightly constrained by the adjacent hillslopes than the old-growth reach. Low areas that appear to be abandoned channels choked with logging debris occur alternately on the right and left sides of the active channel, but the debris and dense vegetation typical of regrowth in clearcuts made detailed mapping of these features impractical. Other than some sand and some possibly rafted deposits of small organic debris, there was little evidence of much recent activity in these suspected former channels.

The riparian zone within the clearcut reach contains abundant willow (*Salix spp.*) along the channel margins and on mid-channel bars, as well as some vine maple (*Acer circinatum*) and mature red alder (*Alnus rubra*). The channel exhibits a bit of a tendency to bifurcate within this reach. Secondary channels active only during moderately high flows are present along the right channel margin in the vicinity of XS 106 to 108 and XS 110 to 112, separated from the main channel by a low surface vegetated with willow and alder (Figure 9.5). Farther downstream, two channels of nearly equal width (the left channel being somewhat higher and hence not active at very low flows) are present between XS 115 and 117 (Figure 9.4); these channels are separated by a willow-covered bar with one or two mature alders at the downstream end.

Upstream of the road crossing, Mack Creek drains the largest uncut portion of the Andrews Forest. Its forest cover, due to the north-facing aspect, has experienced no fires in 450+ years and is unusually rich in old-growth relative other uncut areas of the Andrews (Weisberg, 1998). Hence, the MAC site is unique within the Andrews Forest and probably has few analogues in the Western Cascades. The MCC site, in contrast, may be more representative of many 3rd-order streams on public forest land today.

### 9.1.4   MIDDLE LOOKOUT CREEK SITE

The middle Lookout Creek (LOM) site consists of 11 irregularly spaced cross sections in a 300-m long reach (Figure 9.6). It is located roughly in the middle of the Lookout Creek watershed on 4th-order Lookout Creek (Figure 3.1) at an elevation of approximately 575 m. The upper of two low elevation mainstem Lookout Creek sites, its upstream drainage area, estimated from 30-m DEM, is 31.7 km$^2$, approximately half that of the entire Lookout Creek watershed and a little more than five times that of the Mack Creek sites (Table 9.1). The average channel gradient is 3.2%, or about one third of the gradient at the Mack Creek sites and less than a fifth of the gradient of the Cold Creek site. The average channel width is approximately 24.7 m, roughly double that of the Mack Creek sites and nearly 5 times that of the Cold Creek site.

Two key characteristics of the LOM site are the absence (mostly) of hillslopes adjacent to the channel and the abundance of large, fluvially transported LWD. Among cross section sites, the LOM site is unique in being mostly unconstrained by surrounding topography (Table 9.1, Figure 9.7). The channel is adjacent to a hillslope only on the left bank of the lower 100 m of the reach. Elsewhere the channel is bordered by extensive floodplain surfaces (mostly less than 1.5 to 2 m above the low-flow channel), covered with old-growth conifer and mixed conifer-hardwood forest. On the left bank, the channel is bordered by a floodplain approximately 1 to 2.5 m (mostly <1.5 m) above the current summer low-flow water surface. This surface is vegetated with old-growth Douglas fir, hemlock, cedar, and bigleaf maple, extending from approximately 75 m upstream of the uppermost cross section down to XS 7, a distance of approximately 260 m. At the upstream end of this surface, a large side channel branches off from the main channel and follows a large arc to the south (presumably a former meander bend of Lookout Creek), returning to the main channel just upstream of the x-post for XS 7 and 8 (Figure 9.6, location E). The entrance of the side channel (not shown in Figure 9.6) is partially blocked by LWD and sediment, and no surface water enters under summer low flow conditions, although some flow in the channel is maintained via subsurface flow. At approximately the southernmost extent of the arc, a small perennial tributary flows into the side channel. The outside
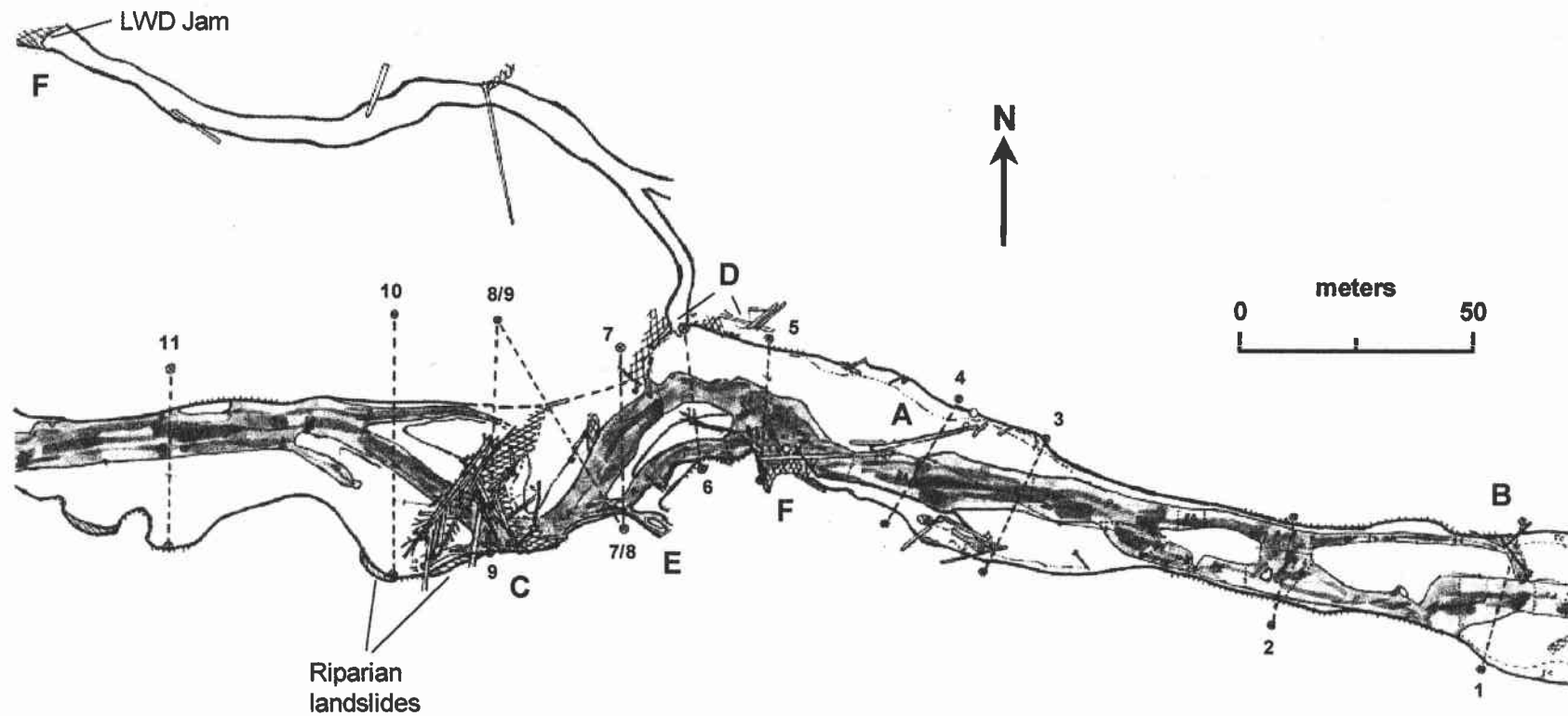
Figure 9.6. Map showing channel features and cross section locations at the middle Lookout Creek (LOM) site, fall 1996. Letters identify locations of features referred to in text: A – large log anchoring up- and downstream bars; B – marginal LWD accumulation anchoring upstream bar and protecting downstream bar; C – channel-spanning LWD jam formed in February 1996 flood; D – entrances to back channels in floodplain, plugged by sediment and woody debris; E – junction of combined back channel and small tributary with main channel; F – marginal LWD accumulation anchored by channel-spanning log; G – LWD jam in back channel emplaced in February 1996 flood.
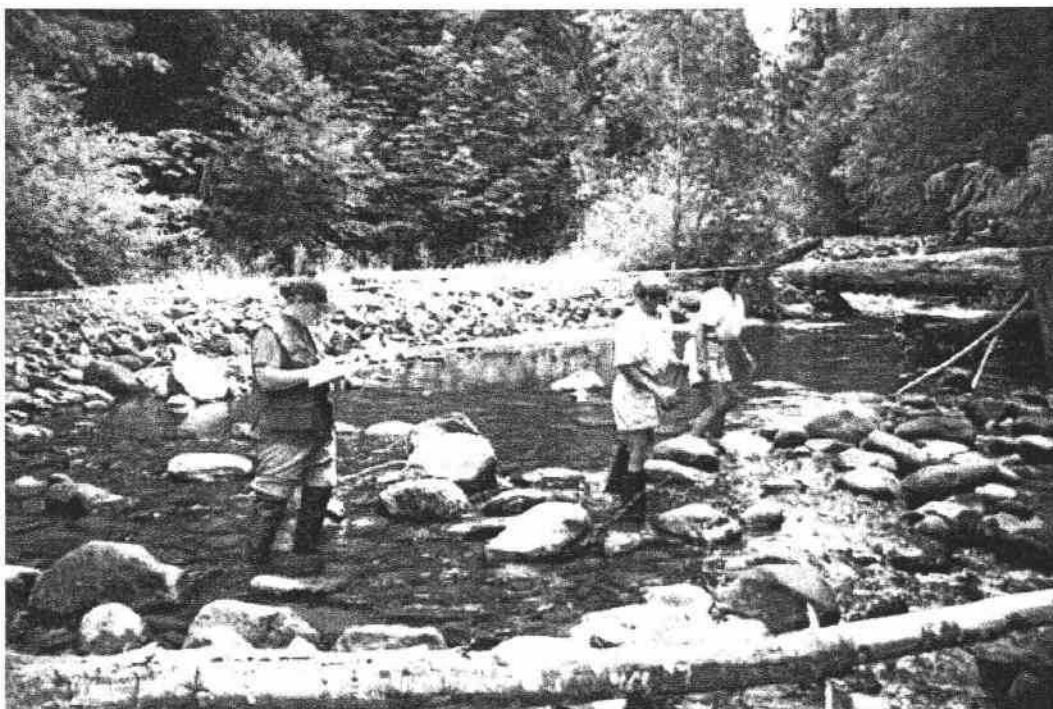
Figure 9.7. View of stream channel and adjacent forested floodplain at the middle Lookout Creek (LOM) site (near location A in Figure 9.6).

edge of the side channel and the floodplain surface it bounds is marked by a short, abrupt 6 to 10-m high slope that is most likely the edge of a dissected alluvial fan.

Downstream of where the side channel rejoins the main Lookout Creek channel, the left bank of the channel takes on a scalloped appearance and becomes a sheer wall at the foot of a steep hillslope. Since the February 1996 flood, portions of the bank where the current has been forced against the bank by a massive accumulation of LWD and associated sediment (Figure 9.6, location C) have slumped down into the channel carrying several large conifers with them.

On the right (north) bank, bank height decreases fairly abruptly from $\geq 2$ m upstream to <15 m downstream of XS 2. A forested flooplain surface extends approximately 50 to 125 m north of the channel edge, to the edge of Road 1506 in the upstream portion of the reach or the edge of a 2 to 4-m high terrace bordering the downstream end of the reach. A network of back channels, some of which are shown in Figure 9.6, dissect the forested floodplain surface downstream of XS 5; less well-

defined channels and evidence of lateral overflow from the main channel extend upstream as far as XS 3. Major back channel entrances, partially plugged by LWD and sediment, are located by cross section posts 5Z and 6Z in the central portion of the LOM reach (Figure 9.6, location D). The main back channel shown in Figure 9.6 is lower than the main Lookout Creek channel, and its entrance by XS 6 is less than one meter above the summer low-flow water surface. This back channel has year-round flow via hyporheic flow from the main channel.

As noted above, the LOM site contains abundant LWD including old-growth conifer logs. Unlike the Cold Creek and Mack Creek sites, most of the LWD within the LOM reach, including large logs, has been fluvially transported, and is concentrated in large marginal or channel-spanning accumulations. Many of the logs have cut ends. A major feature of this reach is a massive accumulation of LWD along the right (north) bank of the channel extending downstream from the vicinity of XS 5 (Figure 9.6, location D) and spanning the channel in the vicinity of XS 9 (Figure 9.6, location C). Much of this LWD predated the February 1996 flood and probably was emplaced by the 1964 flood, but a channel spanning accumulation, which partially blocks the main channel in the vicinity of XS 9, was created by the 1996 flood.

The LOM site is typical of many $4^{th}$-order reaches in the western Cascades in that it is downstream of dozens of clearcuts (but is not bordered by any). It is atypical in its geomorphic setting within a wide alluvial valley floor segment caused by deposition upstream of a massive earthflow (Section 9.1; Swanson and James, 1975a). Wide valley floors are more typical of the Washington Cascades, which have been more heavily glaciated. The LOM site is upstream of most documented debris flows (Figure 9.1), and where the valley floor is wide tributary debris flows often stop before reaching Lookout Creek (Grant and Swanson, 1995), so it is probably not strongly affected by mass movement processes. Several known active earthflows occur upstream of the Mack Creek confluence, but are too far upstream to have much direct influence on the channel at the LOM site.

### 9.1.5 LOWER LOOKOUT CREEK SITE

The lower Lookout Creek (LOL) site consists of 14 cross sections along a 470-m long reach of 5th-order Lookout Creek (Figure 9.8) located approximately 450 m upstream of the Lookout Creek gaging station (Figure 3.1). The upstream drainage area is approximately 61.5 km$^2$, very nearly double that of the LOM site, while the average channel gradient is slightly less than half that of the LOM site at 1.5% (Table 9.1). With an average channel width of approximately 27.3 m, however, it is only slightly wider than the LOM site (24.7 m), although the lower two-thirds of the reach is slightly wider (29.3 m).

A sharp (>90°) left bend, in which the channel has been pinched against a bedrock wall on the right bank by an alluvial fan (currently inactive) on the left bank, divides the reach into two distinct parts (Figure 9.8, location A). In the upper part (not shown in Figure 9.8), the stream flows to the northwest, bending slightly toward the west before entering the sharp southward bend. The channel runs along the foot of a steep hillslope on the right, while the left bank is bordered by a more gently sloping surface that is probably an inactive alluvial fan. Downstream of the sharp bedrock bend, the channel abruptly widens and the stream flows nearly due south for approximately 230 m. A large, high bar, approximately 130 m long by up to 20 m wide (Figure 9.8, location B), separates the current channel along the east bank from the former main channel (abandoned during the February 1996 flood) along the west bank. Downstream of this bar, the channel narrows and bends approximately 25° toward the west. About 90 m downstream of this second bend, the channel enters a narrow bedrock gorge just below the lowermost cross section (XS 1, Figure 9.8).

Downstream of the bedrock bend, the left (east) bank of the channel is a 4- to 6-m high terrace in which fluvial sediments (presumably older Lookout Creek sediments) unconformably overlie a debris flow deposit, which presumably originated in watershed 2 (WS 2; Figure 3.1), and varved glaciolacustrine sediments (Gottesfeld et al., 1981). Gottesfeld et al. reported a piece of wood from the debris flow deposit to have a carbon 14 date of greater than 35,500 years B.P. The stream appears to be actively eroding the terrace for approximately 200 m from the bedrock bend

(a) July 1990          (b) fall 1996
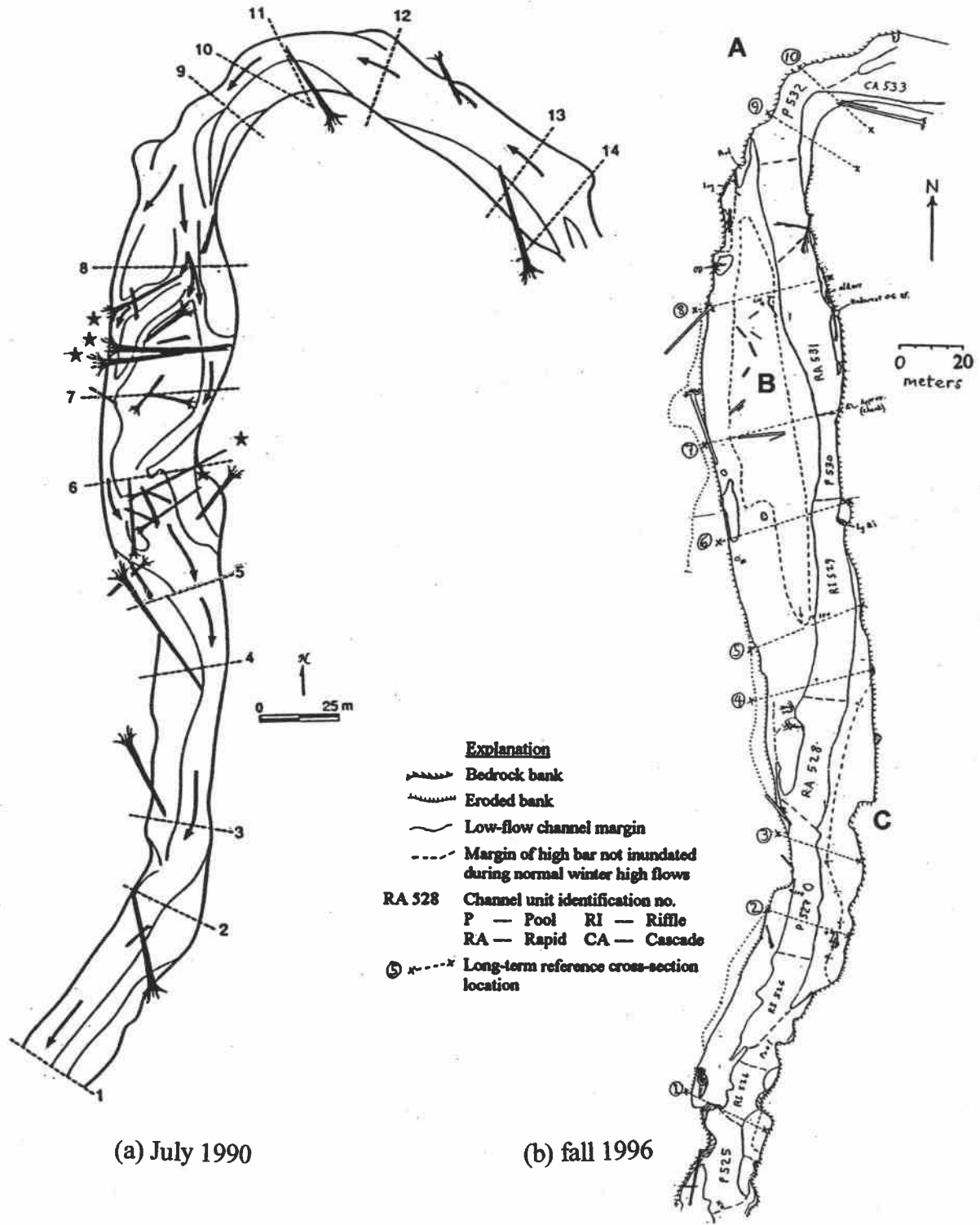
Figure 9.8. Maps of channel features at the lower Lookout Creek (LOL) site: (a) July 1990 (from Nakamura and Swanson [1993]); (b) fall 1996 (by author). Letters identify locations of features referred to in text: A – bedrock-constrained bend; B – large separating abandoned channel (west of bar) from new channel formed by the February 1996 flood; C – bedrock outcrop at constriction and bend in channel.

downstream to a bedrock projection just upstream of XS 3 (Figure 9.8, location C). On the right (west) bank downstream of the bedrock bend, a low terrace or floodplain surface approximately 1.5 to 2.5 m above the low-flow channel extends downstream from the vicinity of XS 8 to XS 1, reaching a maximum width of about 30 m. This surface is covered with old-growth conifer forest and is bordered on the west by a high terrace on which the H.J. Andrews headquarter facilities are located.

Cross sections in the LOL reach are quite irregularly spaced, particularly in the upper part of the reach. In the upper sub-reach above the sharp bend, the two uppermost cross sections (XS 13 and 14) are only approximately 25 m apart, followed by a more than 60-m gap to the next cross section. This is followed by three closely spaced cross sections (XS 9 to 11) within the bend, and then by eight somewhat irregularly spaced cross sections in the next approximately 300 m downstream of the bend (Figure 9.8).

Prior to the flood of February 1996, LWD was fairly abundant within the portion of the LOL reach downstream of the bedrock bend, including a number of old-growth Douglas fir and cedar logs, which spanned the channel or projected from the banks into the channel, but most of this wood was evacuated from the reach during the flood. Changes in LWD and the channel planform over time at the LOL site are discussed in Section 10.2.5.

The LOL site differs from the LOM site in that it is much more highly constrained by adjacent valley walls and valley floor landforms (i.e., alluvial fans and terraces), although the abrupt local widening in channel and valley floor width downstream of the sharp bend at the LOL site may cause the portion of the reach downstream of this feature to behave more like an unconstrained reach. The LOL site is downstream of numerous documented debris flows, many of which have reached Lookout Creek (Figure 9.1). One unique aspect of the LOL site is the clearing for the Andrews Forest headquarters to the northwest, which may conceivably have exacerbated windthrow in this reach, causing LWD input to be higher than it otherwise would be. Overall, the LOL site is probably more representative of "typical" 4th to 5th-order mainstem channels in the western Oregon Cascades than is the LOM reach.

## 9.2    Field Methods—Historical Data

### 9.2.1    Cross Section Monitoring

Reference cross sections were first established in 1978 at the lower Lookout Creek (LOL), middle Lookout Creek (LOM) and Mack Creek old-growth (MAC) sites, and in 1980 and 1981, respectively, at the Cold Creek (COC) and Mack Creek clearcut (MCC) sites (Figure 3.1). Between 11 and 20 cross sections were established at each site (Table 9.1). Cross sections were irregularly spaced to sample a range of channel environments (pools, riffles, etc.). Endpoints of each cross section were marked by steel fence posts or in some cases (on bedrock or resistant cohesive banks) by an eyebolt or a steel rebar stake. Cross sections were resurveyed annually between 1978 and 1999 except in years which did not have significant storms (Table 9.2). The longest interval between re-surveys was five years, between 1990 and 1995, a hydrologically quiescent period during which only the 1995 peak discharge approached the mean annual flood in Lookout Creek. Beginning in 1995, black-and-white photographs of each cross section, typically one upstream and one downstream view, were routinely taken during cross section surveys.

Cross sections were surveyed according to a standard protocol using an auto-level (an instrument with an optical self-leveling mechanism that maintains a true level line-of-sight once the instrument is approximately leveled by hand) and a telescoping fiberglass stadia rod graduated in 0.5-cm increments, as described in Section 3.2. However, the equipment and protocol used in surveying the cross sections changed somewhat over time, a fact which should be taken into account when interpreting the data. Up until the mid-1980s, the cross sections were surveyed using a Dumpy level, an instrument which can be used for either level or inclined sightings. This instrument required careful attention to maintaining a level line of sight to achieve accurate results. Inclined sightings (in which the angle between the telescope line-of-sight and the horizontal plane was recorded and a trigonometric correction applied to the elevation data) were occasionally used during this period when vertical relief within the cross section exceeded the height of the stadia rod. An auto-level was

Table 9.2.  Summary of cross section data availability.

| Water Year | Max. $Q_{pk}$ $(m^3/s)^{(1)}$ | Site | | | | |
|---|---|---|---|---|---|---|
| | | LOL | LOM | MCC | MAC | COC |
| 1978 | **86.4** | Yes | Yes | | Yes | |
| 1979 | 32.8 | | | | | |
| 1980 | 44.2 | Yes | partial | | Yes | Yes |
| 1981 | **62.9** | Yes | Yes | Yes | Yes | Yes |
| 1982 | 49.6 | Yes | Yes | Yes | Yes | Yes |
| 1983 | 41.6 | | | partial | Yes | |
| 1984 | **59.5** | Yes | Yes | Yes | Yes | Yes |
| 1985 | 32.0 | Yes | Yes | Yes | Yes | Yes |
| 1986 | **76.5** | Yes | Yes | Yes | Yes | Yes |
| 1987 | 27.5 | | | | | |
| 1988 | 30.9 | Yes | Yes | Yes | Yes | |
| 1989 | 47.6 | Yes | Yes | | | |
| 1990 | 55.5 | Yes | Yes | Yes | Yes | |
| 1991 | 28.6 | | | | | |
| 1992 | 31.4 | | | | | |
| 1993 | 34.5 | | | | | |
| 1994 | 23.4 | | | | | |
| 1995 | 50.1 | Yes | Yes | Yes | Yes | Yes |
| 1996 | **226.5** | Yes | Yes | Yes | Yes | Yes |
| 1997 | **84.4** | Yes | Yes | Yes | Yes | Yes |
| 1998 | 41.6 | Yes | Yes | | | |
| 1999 | 55.8 | Yes | Yes | | | |
| Avg.[2] | 56.1 | | | | | |

Notes

Yes = cross sections surveyed in indicated year

partial = subset of cross sections surveyed in indicated year

[1] Maximum instantaneous discharge during year at Lookout Creek gage.  Values in **boldface** exceed mean annual $Q_{pk}$.

[2] Mean annual instantaneous peak discharge for 1950-98.

first used for surveying the cross sections in either 1986 or 1988. In an effort to improve data consistency, the cross section survey protocol was modified and standardized in 1986 (Henshaw, 1986). Prior to to this time, elevations were measured at irregular intervals along the line of section at slope breaks and other points selected to capture important topographic and geomorphic features and changes in substrate type. The frequency of surveyed points along each cross section varied considerably from year to year, resulting in a variable degree of resolution in characterizing the channel cross-sections. The categories used to classify the substrate material also varied from year to year until 1982, when substrate codes were standardized and data from previous surveys were reclassified to conform to the new scheme.

In addition to standardizing the sampling interval, several additional steps were taken to improve data quality in 1986. Cross section end posts were better anchored (where necessary) and labeled; attachment points on each cross section end post were identified and marked to ensure that the tape would be at least approximately level (so that horizontal distance measurements would be accurate and consistent between survey dates); and a check of the cross section length was made prior to surveying to ensure that it was consistent with previously measured values. Previously, no effort was made to ensure that the tape was approximately level (or to correct the horizontal distance for the effects of an inclined tape) or that the measured section length matched previous survey data. At several cross section locations at the lower Lookout Creek site, where one end post was located on a high terrace, intermediate posts were established lower on the bank in 1986 at an elevation closer to that of the post on the opposite bank; the intermediate posts subsequently served as the new cross section end points.

Beginning with the 1995 survey, modified Wolman (1954) pebble counts were performed in conjunction with the cross section surveys to characterize bed material surface particle size and its spatial and temporal variability. Pebble counts were performed at each cross section location at the Lookout and Mack Creek sites and within 3 sub-reaches at the Cold Creek site, where the small channel size makes individual cross-section based counts impractical. Pebble counts consisted of

measuring the intermediate-axis diameter of 100 particles selected at random from the streambed within the active channel floodway and within approximately one to two meters up- and downstream of the cross section line. Particles were selected by traversing the channel along the cross section line and reaching down with one finger while looking away from the streambed to avoid biasing selection. Each particle was measured to the nearest 5 mm (or the nearest 1 mm for particles less than about 5 cm in diameter) using a steel tape measure. Particles less than 2 mm in diameter (i.e., sand) were recorded simply as <2 mm. For large partially buried particles, the length of the apparent intermediate axis of the exposed portion of the particle was measured.

### 9.2.2 STREAMFLOW MONITORING

The U.S. Geological Survey (USGS) has operated a stream gage near the outlet of the Lookout Creek basin since 1950, and several tributaries have been gaged by the U.S. Forest Service (USFS) using flumes installed between 1952 and 1980 as part of a series of paired watershed experiments, in which the hydrologic response of small watersheds manipulated by various treatments (e.g., partial or total clearcutting) was compared with that of control (unaltered) watersheds (Jones and Grant, 1996). Discharge data from the Lookout Creek gage and the control watershed gages operated by the USFS were used in this study. The locations of the gages are shown in Figure 3.1, and characteristics of the gaged watersheds are summarized in Table 9.3. Data were obtained from the H.J. Andrews Long-Term Ecological Research (LTER) Site online database (http://www.fsl.orst.edu/lter/ datafr.htm) and from the USGS National Water Information System database (http://waterdata.usgs.gov/nwis-w/US/).

## 9.3    Field Methods—Supplemental Data

Additional field data were collected between the fall of 1996 and the fall of 1998 to more completely characterize channel morphology within the study reaches. Field work performed at each study reach included (1) a survey of the cross section

Table 9.3. Characteristics of gaged watersheds used in this study.

| Characteristic | Lookout | Mack | WS 2 | WS 8 | WS 9 |
|---|---|---|---|---|---|
| Drainage area, km$^2$ | 62.4 | 5.8 | 0.60 | 0.21 | 0.09 |
| Elevation at gage, m | 428 | 758 | 548 | 993 | 432 |
| Max. elevation in watershed, m | 1620 | 1610 | 1070 | 1170 | 700 |
| Year established | 1950 | 1980 | 1953 | 1964 | 1969 |
| Years of record (through 1998) | 49 | 19 | 46 | 34* | 29* |
| Max. historical peak discharge, m$^3$/s | 227[#] | 9.35 | 1.30 | 0.41 | 0.13 |
| Mean annual peak discharge, m$^3$/s | 56.1 | 5.16 | 0.47 | 0.16 | 0.07 |
| Min. annual peak discharge, m$^3$/s | 8.30 | 2.37 | 0.09 | 0.04 | 0.02 |
| Max. peak unit area discharge, m$^3$/s/km$^2$ | 3.63[#] | 1.61 | 2.16 | 1.90 | 1.56 |
| Mean peak ann. unit area discharge, m$^3$/s/km$^2$ | 0.90 | 0.89 | 0.77 | 0.74 | 0.86 |
| Min. peak ann. unit area discharge, m$^3$/s/km$^2$ | 0.13 | 0.41 | 0.16 | 0.19 | 0.25 |

* 1998 data not available for WS 8 and WS 9
[#] estimated value

endpoint stakes; (2) mapping the channel including the margins of the low flow channel and active channel floodway, channel unit types, the positions of large logs and woody debris accumulations, and other salient channel features; and (3) surveying a high-resolution longitudinal profile of the channel thalweg.

## 9.3.1 CROSS SECTION ENDPOINT SURVEYS

End post locations for each cross section were surveyed during the summer of 1997 to accurately establish the spatial relationship of the cross sections to one another. The relative elevations and map locations of the cross section reference posts (measured at the ground surface) were surveyed using a builders' auto-level and laser theodolite as described in Section 3.3.1.

### 9.3.2 MAPPING OF STUDY REACHES

Each study reach was mapped by tape-and-compass (lower and middle Lookout Creek, Figures 9.8 and 9.5, respectively), laser theodolite (Cold Creek, Figure 9.3), or a combination of the two methods (Mack Creek, Figure 9.4). In tape-and-compass surveys, a fiberglass surveying tape was stretched tautly between temporary steel rebar survey stakes driven into the streambed (or, in some cases, into large logs in the channel). The bearing of the baseline tape was then carefully measured using a staff compass graduated in ½-degree increments. Locations of fixed reference points (e.g., cross section end posts) were determined by measuring the distance between the point of interest and two or more points on the tape using a second fiberglass tape, noting which side of the baseline (left or right relative to a downstream-facing observer) the feature was on to obtain a unique plotting location. Other points of interest (points along the channel margins, endpoints of logs within the channel, etc.) were surveyed by measuring the perpendicular distance from a known point on the baseline and recording the baseline tape distance, perpendicular distance, and direction (left or right of the tape, facing downstream). All measurements were recorded to the nearest 0.1 m. A handheld compass was used to ensure that the measurements were made perpendicular to the baseline tape. Points along the edge of the wetted channel at the time of mapping (low-flow channel) and the margin of the active channel floodway were surveyed at intervals sufficient to define the channel margins (typically ¼ to ½ channel width or less).

The surveyed points were plotted by hand on water-resistant paper in the field or office at a scale of 1:1000 or greater. The channel margins were then sketched in in the field, and details such as large boulders or logs, bedrock outcrops, and scoured or undercut banks were added to the map.

For the Mack Creek and Cold Creek sites, a laser theodolite was used to survey the locations of points along the active channel floodway margins in a manner similar to that described below for the longitudinal profile surveys. These points were marked in the field by flagging tape or survey flags bearing unique ID numbers noted on the survey data form. After the map coordinates of these points relative to an arbitrary

starting point (one of the cross section posts) had been calculated and plotted by computer, the plot was taken into the field and the details of the channel margins were sketched in by hand. Further details (logs, large boulders, channel unit boundaries) were then added by tape-and-compass survey using the channel margin flags as reference points.

### 9.3.3 LONGITUDINAL CHANNEL PROFILE SURVEYS

Cross-sections at best offer only an incomplete characterization of channel morphology in high-gradient streams such as those within the Lookout Creek watershed, which tend to develop a stepped structure in longitudinal profile (Grant et al., 1990). Therefore, a high-resolution longitudinal profile was surveyed along the channel thalweg for the entire length of each of the study reaches to supplement the cross sections. At Mack Creek, a longitudinal profile of approximately 1 km of the channel, including both the old-growth and clear-cut sites, was surveyed (Figure 4.1).

The survey was performed using the laser survey instrument described in Section 3.3.1. One member of the 2-person survey crew operated the instrument and recorded all data, while the other selected points to be surveyed and held the staff bearing the reflecting target vertically at the point to be surveyed. The person on the staff also estimated the water depth to the nearest centimeter at each location using 5-cm gradations on the reflector staff, and noted the substrate type. For each point occupied, the following data were recorded: horizontal distance, vertical distance, compass bearing, staff height (to center of reflecting target), water depth, and substrate code(s).

Substrate categories were the same as those used for the cross-section surveys. However, rather than recording the substrate immediately beneath the reflector staff, the dominant substrate within a 25-cm radius around the staff was recorded. If two substrate types each comprised greater than 1/3 of the area within a 25-cm radius, based on a visual estimate, a primary and secondary substrate type were recorded. To maintain data consistency, field crew members kept the same roles throughout the duration of the project.

At the Mack and Cold Creek sites, points were selected along the main channel thalweg at intervals of approximately one meter, or a smaller interval where necessary to characterize abrupt changes in channel slope or elevation—e.g., at the crest and base of abrupt steps in the longitudinal profile. At the Lookout Creek sites, a slightly longer interval—up to 1.5 m—was used. At points where the flow divided around a mid-channel bar, the profile followed the larger channel (or in some cases both channels). The location of any steps greater than about 30 cm in height was noted in the comment column of the field notes. When traversing pools, it was attempted to include the upstream and downstream endpoints of the pool as well as the deepest point located along the thalweg.

Survey data were entered into a spreadsheet, where the measured compass bearings and horizontal and vertical distances were used to calculate the coordinates (x,y,z) of each point with respect to an arbitrary reference point (one of the previously surveyed cross section end posts).

## 9.4 Corrections and Adjustments to Cross Section Survey Data

The historical cross section data contain a number of sources of potential measurement error or uncertainty in comparing between successive cross section surveys. A systematic process of data verification (i.e., error detection and correction; Section 9.4.1), adjustment of cross section profile alignment (Section 9.4.2), and filtering to remove errors associated with LWD (Section 9.4.3) was implemented to minimize these potential errors and maximize the amount of useful information that could be extracted from the cross section profiles. In addition, the data were scaled (Section 9.4.4) to allow between-site comparisons of channels of larger and smaller channels. Resulting *un*scaled cross section plots after error correction, alignment, and filtering are included in Appendix B.

Cross section survey data for 1996 and prior years were obtained by the author from the H.J. Andrews LTER database (http://www.fsl.orst.edu/lter/datafr.htm) and converted from units of centimeters to meters prior to processing. Data from 1997 and

subsequent years were entered and proofed from the original field notes by the author prior to the steps described below.

### 9.4.1 Sources of Error and Uncertainty

Surveying errors can affect either the horizontal coordinate, the vertical coordinate, or both for individual data points in cross section profiles. Measurement errors affecting the vertical or z-coordinate can result from incorrectly reading the level at which the telescope crosshair intersects the stadia rod. Surveying errors that can affect the horizontal or x-coordinate can result from incorrectly reading the position of the rod on the tape, which is particularly a problem when the cross section tape is high above the channel bed. Failure to hold the stadia rod vertically or incorrectly or illegibly recording the data can result in both horizontal and vertical errors.

Perhaps the most common—or at least the most readily detectable—error was recording the wrong value for the first digit (i.e., the meter mark) of the crosshair reading, due to the fact that often no meter mark is within the field of view of the level telescope and only the decimeter and centimeter markings can be seen, particularly on short distance shots where the field of view is small. The likelihood of misreading the meter value is highest when transitioning from one meter interval to the next higher or lower interval—for example, if a series of points with crosshair values in the range of 1.8 to 1.9 m are followed by a point at, say, 2.17 m, the value might be misread (or mis-recorded) as 1.17 m if the change in the first digit is missed. Fortunately, this error is often readily apparent when inspecting the cross section profile plots (Figure 9.9[a]), particularly if only one or two points are affected and the profile did not otherwise exhibit large changes from the previous survey, because abrupt spikes or troughs with a 1-m amplitude are rare within channels and are typically attributable to logs or large boulders (which tend to remain in the same place for a long time). Where such spikes or troughs were present during one survey but were absent in preceding and subsequent surveys, the z-coordinate was corrected by ± 1 m on the
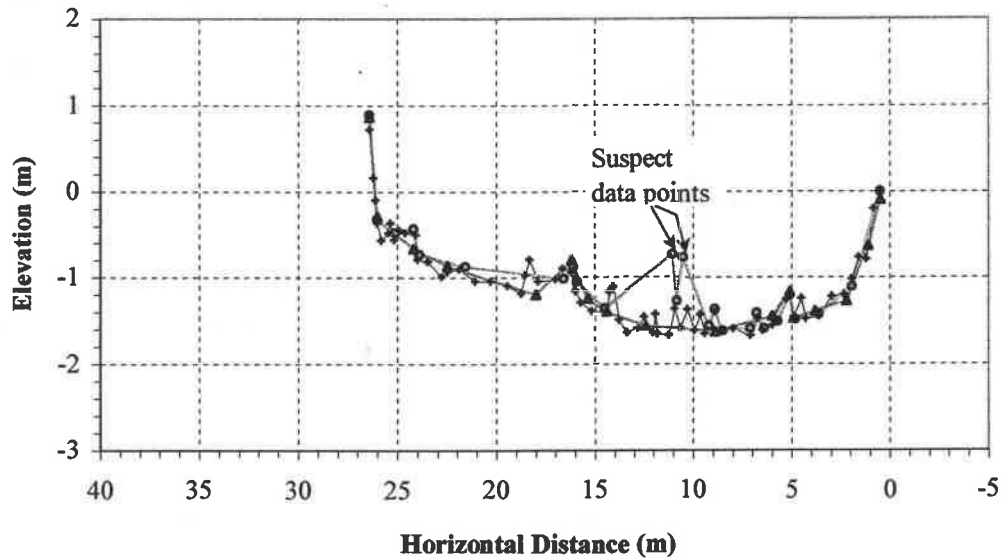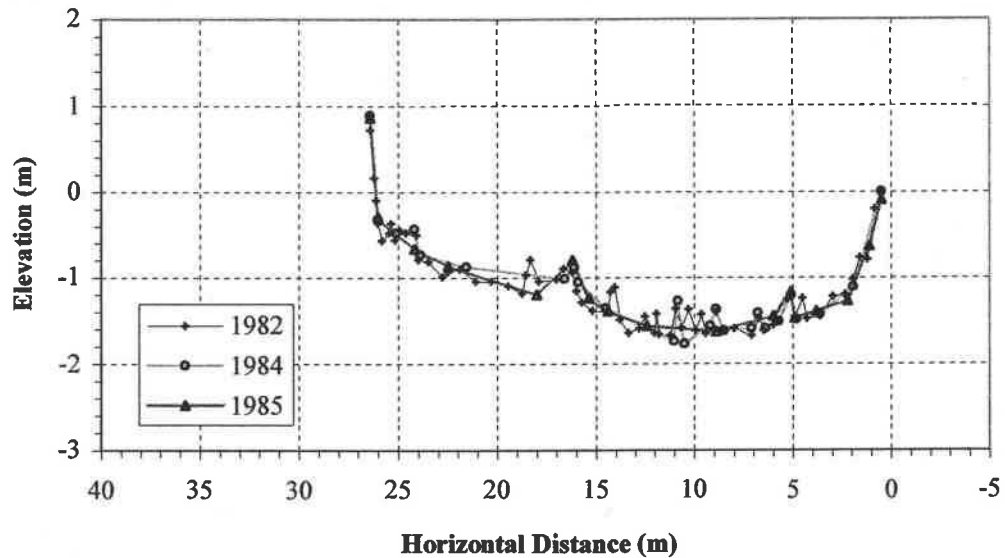
Figure 9.9. Correcting inferred surveying errors from inspection of cross section profile plots. (a) Uncorrected plot; two suspect data points create large apparent change between the 1984 profile and both the 1982 and 1985 profiles. Apparent change is magnified by sparsity of data points in the 1984 and 1985 surveys. (b) Corrected plot. The elevations of the two suspect points have been adjusted by -1.00 m to correct the inferred surveying error. The corrected plot shows little apparent change between the 1984 and 1985 profiles; small apparent differences between the 1982 profile and the later profiles are mainly due to the higher resolution of the 1982 survey.

assumption that an error had been made in reading or recording the first digit of the crosshair intercept (Figure 9.9[b]).

Other surveying errors are more difficult to detect and correct. Errors in the second or third digit of the crosshair intercept cannot be detected by inspection of cross section profiles; however, errors of 0.1 m or less are relatively insignificant and would not affect interpretation of the profile data. Errors in the horizontal or x-coordinate have little effect where the streambed is flat or gently sloping along the line of the cross section, but can significantly affect the apparent position of steeply sloping surfaces such as the stream bank or the edge of a bar.

Failure to hold the stadia rod vertically during surveying can result in errors in both the vertical and horizontal coordinates (Figure 9.10[a]). The vertical error from this source is generally insignificant; for example, if the rod is 5° out of vertical (an amount readily perceptible to an observer) and the apparent crosshair intercept is 2.00 m, then the true vertical height of the crosshair intercept above the base of the rod is $2.00 \times \cos 5°$ or 1.99 m. However, if the rod leans in a direction parallel to the tape and the tape crosses the rod at a height of 2 m, then the difference in the position of the base of the rod (vertically beneath the tape) and the position of the rod where it crosses the tape would be $2.00 \times \sin 5°$ or 0.17 m. If the rod crossed the tape at a height of 5 m (not uncommon in early surveys of some profiles at the lower Lookout Creek site), the error in the x-coordinate would be 0.44 m. Exacerbating this problem is the fact that the telescoping stadia rods used in surveying the cross sections bends at the joints between segments (Figure 9.10[b]), making it often difficult or impossible to hold the rod truly vertical when it is extended beyond the first 2 segments (about 3 m).

The factors discussed above affect the accuracy of the x- and/or z-coordinates of individual points within a cross section profile. Other sources of error affect the entire profile. By far the most important consideration in this regard is the lack of a true fixed reference point for each profile. Although the profile endpoints were monumented in the field by relatively permanent posts or stakes, these markers do not define a precise point in three-dimensional space (Figure 9.11). In essence, each section has two possible reference points—the ground surface at the base of each end post or stake. However, since the ground surface or bank in which the end posts or

**(a)**



$$z = z' \cos \theta$$
$$\Delta z = z' (1 - \cos \theta)$$
$$\Delta x = d \sin \theta$$

**(b)**
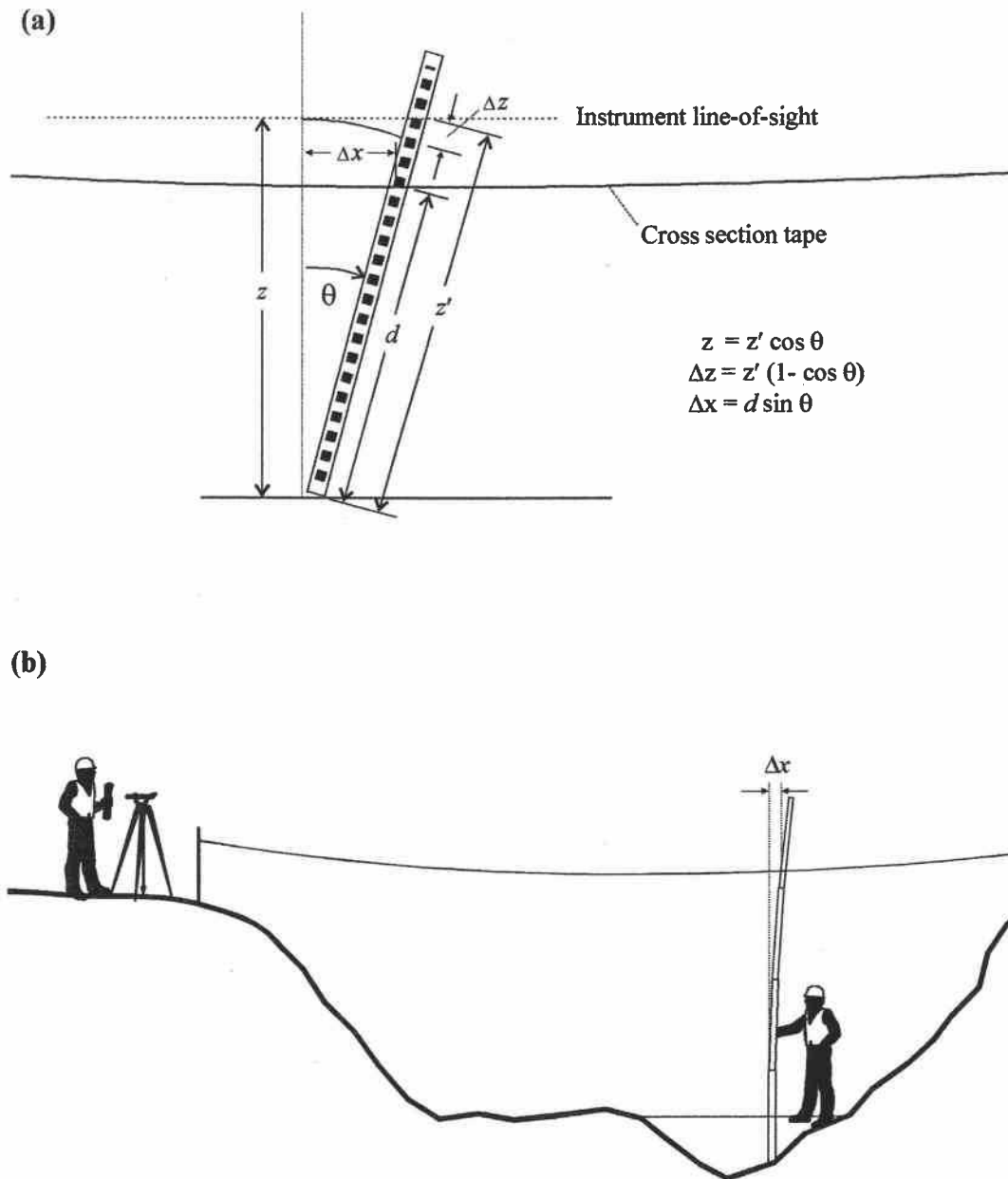


Figure 9.10. Effects of stadia rod lean on cross section survey errors: (a) errors in vertical ($z$) and horizontal ($x$) coordinates resulting from non-verticality of a straight rod; (b) error in measuring the horizontal position of a segmented stadia rod due to hinging at segment joints.
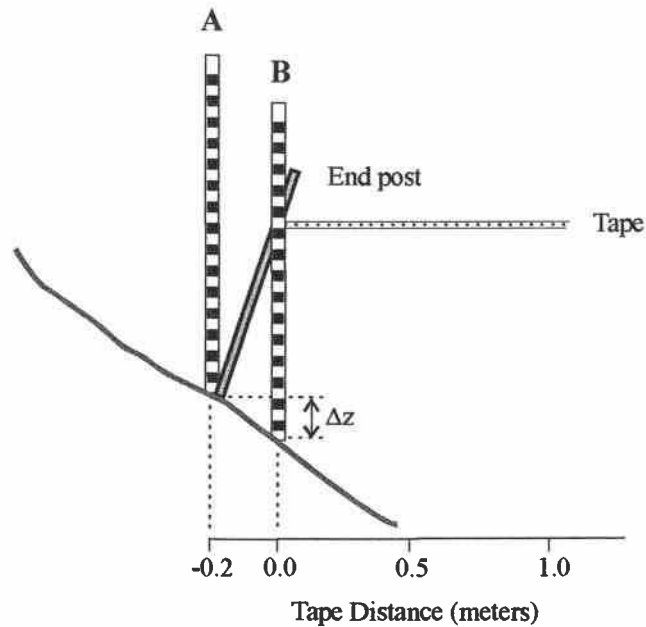
Figure 9.11. Effects of cross section end post lean and stadia rod placement on location of cross section endpoint. Positions labeled A and B identify two possible interpretations of the cross section starting point.

stakes are emplaced is typically sloping (in some cases vertical!) and often spongy and/or uneven, and since the end posts are physical objects rather than dimensionless geometric points, the "base of the post" does not precisely specify a unique point in space. Hence, it matters on which side of the post—upstream, downstream, inboard (toward the channel) or outboard (away from the channel)—the stadia rod is placed when surveying the profile endpoints. Unfortunately, no firm criteria for where the stadia rod should be placed when surveying the profile endpoints were ever established.

Other factors, such as post lean, complicate the matter of defining where exactly the endpoint of the cross section lies. In Figure 9.11, the post leans inward (toward the channel), which is a common occurrence (probably due to a combination of soil creep and the tension applied when the tape is stretched between the two posts). The obvious (and most appropriate) place to put the stadia rod in this case is at the base of the post on the inboard side, in which case the correct horizontal distance (x-

coordinate) to use would be the value at the point where the tape crosses the rod at position A, not the value at the point where the tape attaches to the post (i.e., -0.2 m, not 0.0 m). Alternatively, the stadia rod might be placed next to the post at the point of attachment of the cross section tape (position B in Figure 9.11), in which case the correct horizontal distance would be the value where the tape attaches to the post (i.e., 0.0 m in this example). Position A is a better choice than position B, because its location does not change if the tape attachment point or the angle at which the post leans (which depends in part on how much tension is put on the tape) change. However, the tape distance for sightings at the z-post seldom reported as anything other than zero in the historical data, suggesting that either the rod was typically at the tape attachment point (position B in Figure 9.11), or that the tape reading at the attachment point (position B) was used even though the rod was placed at the base of the post (position A). Most likely, in the absence of a clear protocol, different workers probably made different choices over the years.

Failure to correctly level the surveying instrument can also result in systematic errors that affect the z-coordinate values for the entire profile. This is mainly an issue for surveys done prior to 1986, before a self-leveling survey instrument was used (see Section 9.2.1). Correction for this type of error is discussed in the following section.

## 9.4.2 ADJUSTMENTS TO CROSS SECTION PROFILE ALIGNMENT

A series of adjustments were applied to the cross section profiles to correct for horizontal and/or vertical misalignment of successive profiles surveyed at the same location resulting from the causes described above. As a starting point, profiles from consecutive cross section surveys at a given location were aligned by assuming that the zero-point in the horizontal or x direction, defined as the ground surface at the base of the z-post or stake (the post on the right bank, facing downstream), was always the same point in space and assigning it a local elevation or z coordinate of zero. In cases where this did not result in a good alignment between successive cross section profiles (for example, if the ground surface at the z-post was highly irregular, or if the post was washed out and had to be replaced between surveys) the profiles were aligned at the x-

post (on the left bank facing downstream), assuming that *this* represented the same physical point in space. Due to the inexact nature of the reference points and the sources of uncertainty outlined above, however, it was often necessary to further adjust the data to properly align consecutive cross section profiles.

Therefore, four types of corrections were applied to the cross-section data (Figure 9.12), with the default values being zero for additive corrections (cases 2, 3, and 4) and one for multiplicative corrections (case 1):

1. length adjustment, $L_{adj}$: a multiplicative adjustment of the x coordinate to stretch the profile (values greater than 1) or shrink it (values less than 1) (Figure 9.12[a]). This correction is used to match cross section lengths between consecutive surveys having different reported total lengths for which no real change in length was believed to occur.

2. horizontal offset, $x_{adj}$: a constant added to the x coordinate of each point to shift the profile to the right (if positive) or left (if negative) (Figure 9.12[b]).

3. vertical offset, $z_{adj}$: a constant (positive or negative) added to the z coordinate of each point on the cross section to shift the profile up or down (Figure 9.12[c]).

4. tilt adjustment, $\Delta z_{max}/L$: a point-wise, linearly increasing positive or negative additive adjustment to the z coordinate to correct for angular misalignment of cross section profiles attributed an out-of-level instrument line-of-sight (Figure 9.12[d]). This correction was only applied to data from surveys prior to 1986.

For each cross section location, profiles from successive survey dates were aligned by interactively plotting the data and adjusting the above correction factors as necessary, within certain limitations. For each site, the entire time series of cross section surveys was divided into sequences of three or four consecutive survey dates, with the first date of the second and subsequent groupings repeating the last date of the preceding grouping (e.g., 1978, 1980, 1981; 1981, 1982, 1984, 1985; etc.). Profiles for each cross section were then plotted in a series of graphs, one for each time period, allowing the profile for each survey date to be directly compared to the profiles for the next prior and subsequent survey dates. Where profiles for consecutive survey dates

**(a) length adjustment ($L_{adj}$)**

$L_1$
$L_2$
unadjusted
$(x_2, z_2)$
$L_{adj} = L_1/L_2$
$x_2' = x_2 \times L_{adj}$
$z_2' = z_2$

$(x_2', z_2')$
adjusted

— Year 1
— Year 2

**(b) horizontal profile offset ($x_{adj}$)**

$x_{adj}$
unadjusted
$(x_2, z_2)$
$x_2' = x_2 + x_{adj}$
$z_2' = z_2$

$(x_2', z_2')$
adjusted

— Year 1
— Year 2

**(c) vertical profile offset ($z_{adj}$)**

$(x_2, z_2)$
unadjusted
$z_{adj}$
$x_2' = x_2$
$z_2' = z_2 + z_{adj}$

$(x_2', z_2')$  adjusted

— Year 1
— Year 2

**(d) angular (tilt) correction**

$\Delta z_{max}$
$L$
$x_2' = x_2$
unadjusted
$z_2' = z_2 + (\Delta z_{max}/L) \times x_2$
$(x_2, z_2)$

adjusted
$(x_2', z_2')$

— Year 1
— Year 2

Figure 9.12. Adjustments applied to cross section profiles to align profiles surveyed in different years at the same location: (a) length adjustment, $L_{adj}$; (b) horizontal profile offset, $x_{adj}$; (c) vertical profile offset, $z_{adj}$; (d) angular (tilt) correction. In all examples, the profile for Year 2 is being adjusted to align properly with the profile for Year 1. $(x_2, z_2)$ are the horizontal and vertical coordinates, respectively, for a point on the Year 2 profile, while $(x_2', z_2')$ are the coordinates for a point on the adjusted profile.
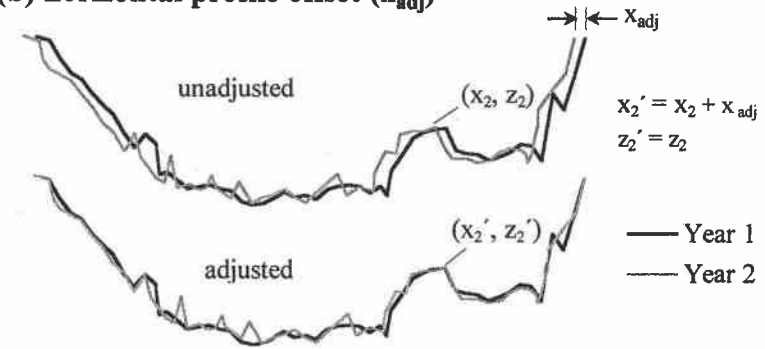
appeared to be misaligned, the appropriate correction factor(s) was (were) adjusted until a satisfactory alignment of portions of the cross section profile which did not exhibit change (stable portions of the channel bank, floodplain surfaces, large boulders or logs, etc.) was achieved. The adjusted cross section profiles are presented in Appendix B.

The length adjustment (Figure 9.12[a]), where necessary, was the first correction applied. The reported total length for a particular cross-section commonly varied by 0.1 to 0.2 m (and occasionally significantly more than this) between consecutive survey dates, even though neither endpoint had been relocated, for reasons discussed in the previous section. These minor discrepancies in profile length typically had a negligible effect on between-year profile comparisons and hence were ignored; the length adjustment was only applied where it noticeably improved the match between portions of the cross section inferred to be stable between surveys.

The lateral adjustment, $x_{adj}$, was applied in two types of cases: (1) when profiles were aligned at the x-post rather than the z-post and the reported tape distance at the x-post was different for the profiles in question, and (2) whenever there appeared to be a constant lateral offset between features with well-defined x-coordinates (such as a near-vertical bank or the top of a boulder), as in Figure 9.12(b).

The most commonly applied adjustment was the vertical constant, $z_{adj}$ (Figure 9.12[c]), which was used to vertically align the cross section profiles. This was often necessary due to the imprecise nature of the elevation control provided by the fixed cross section endpoints, as discussed in the previous section. Stable features having well-defined elevation were used for this purpose, including floodplain surfaces, tops of bars or banks, or the tops of large boulders or logs.

The tilt adjustment was applied in cases where the cross section profile plots suggested that the survey instrument line-of-sight was out of level (Figure 9.12[d]). This correction was applied sparingly, and only on profiles surveyed before 1986, the earliest year in which the auto-level may have been used. Surveys conducted prior to this time were conducted with a manually leveled survey instrument (a Dumpy level), and the practice was to set the instrument up directly over or adjacent to one of the profile end points and sight directly along the line of the cross section. Thus, it is

possible to correct for effects of an out-of-level line-of-sight, assuming a constant angular error, as this correction factor does.

### 9.4.3 DATA FILTERING TO REMOVE ERRORS DUE TO LWD

It is important to filter out logs and woody debris in the cross section profile plots before comparing successive profile plots to infer changes in the channel configuration. Some cross sections cross logs or accumulations of woody debris which are lying on or suspended above the channel bed or banks. Points along the cross section line that are underlain by woody debris (where the stadia rod rests on woody debris during surveying) are not representative of the channel boundary (i.e., the bed or bank). Cross section plots which include such points (especially logs or woody debris which are suspended above the channel) often take on a "spiky" appearance (Figure 9.13[a]) which does not accurately represent the true cross-sectional shape of the channel. In addition, if such points are included in cross section plots, then shifting, rolling, pivoting or other movement of logs or woody debris can result in apparent changes in the channel cross section between consecutive surveys, which may not be representative of actual changes in the configuration of the channel bed or banks.

The substrate code recorded for each data point during cross section surveys was used to identify points to be filtered out of the cross-section profile plot. Points with a substrate code of LG (log), RW (rootwad), RT (root), LS (suspended log), OD (organic debris), or OS (suspended organic debris) were generally excluded from the profile plots if they produced upward spikes (see Figures 9.13 [a] and [b]), but were left in otherwise (i.e., logs or woody debris embedded within and forming part of the channel bed or banks were not excluded from the plots). Points excluded from the profile plots were plotted separately as unconnected points to indicate the presence of logs and woody debris (Figure 9.13[b]).

**(a) unfiltered plot**

Suspended
logs

organic (woody)
debris

log embedded
in bank

logs

log

**(b) filtered plot**
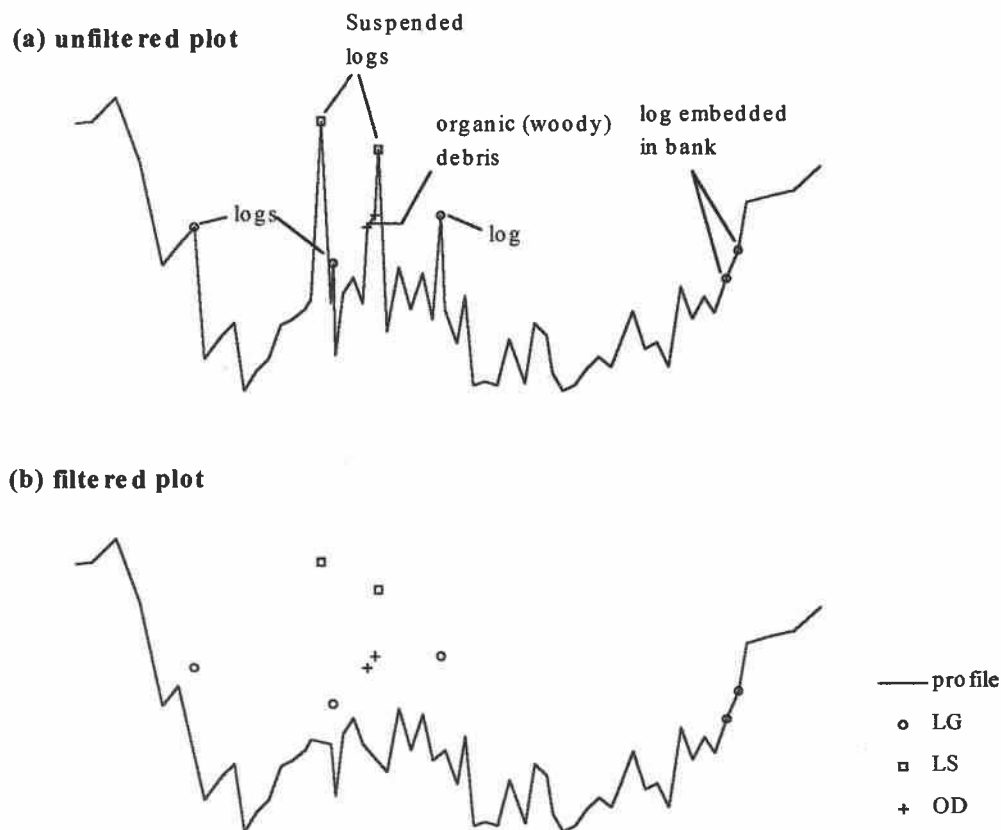
profile
o   LG
□   LS
+   OD

Figure 9.13. Example of the effect of filtering out logs and woody debris on the apparent shape of a cross section profile: (a) unfiltered profile; (b) profile after filtering.

### 9.4.4   SCALING OF CROSS SECTION PROFILES

Two types of scaling corrections were applied to cross section profiles prior to data analysis to adjust for (1) non-perpendicular alignment of cross sections relative to the channel and (2) different widths of cross sections. First, all cross sections that were not perpendicular to the active channel floodway were orthogonalized by multiplying the x-coordinate of each point by the cosine of the angle, $\alpha$, between the cross section line and a line perpendicular to the channel (Figure 9.14). For a straight channel of uniform width, a diagonal cross section has a greater apparent channel width and cross-sectional area than a perpendicular cross section (Figure 9.14). To rectify this, $\alpha$ was estimated graphically using the channel map for each study reach, by drawing a line perpendicular to margins of the active channel floodway that
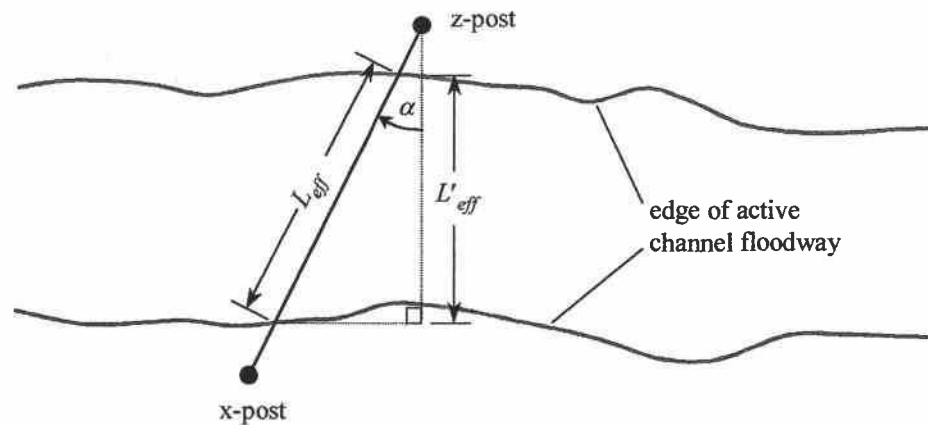
Figure 9.14. Relationship between apparent channel width ($L_{eff}$) along non-orthogonal cross section and channel width measured orthogonal to the channel ($L'_{eff}$).

intersects the cross section profile at approximately its midpoint and measuring the angle between that line and the cross section line on the map. This correction had the effect of shortening diagonally elongated cross sections.

The orientation of the cross section relative to the active channel floodway is of interest for purposes of estimating the magnitude of channel adjustment (i.e., erosion and deposition) or performing hydraulic calculations, since channel changes occur during peak flow events when the entire active channel floodway is occupied and the mean flow direction is determined by the active channel floodway margins rather than the low-flow channel margins. The low-flow channel typically only occupies a portion of the active channel floodway, and often meanders within the active channel floodway margins (Figure 9.15). The orientation of the low-flow channel is therefore often different from the orientation of the active channel floodway, and tends to change more readily. Therefore, cross sections may have had four different arrangements relative to the low-flow channel and the active channel floodway: (1) perpendicular to the low-flow channel (and, hence, perpendicular to flow at the time of the cross section survey) but not to the active channel floodway as a whole (e.g., cross section A-A' at Time 1), (2) perpendicular to both the active channel floodway and the low-flow channel (e.g., cross section C-C' at Time 1),

Edge of active channel floodway

Edge of summer low-flow channel (Time 1)

Edge of summer low-flow channel (Time 2)

A ⸺ A'   Location of cross section profile
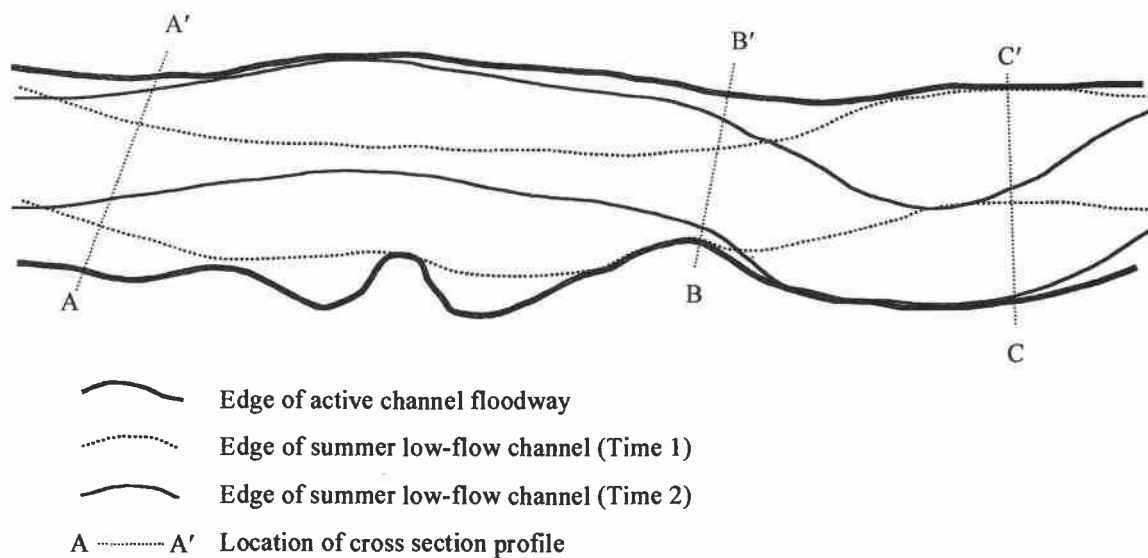
Figure 9.15. Examples of different possible relationships between the orientations of the low-flow channel, active channel floodway, and cross section profiles. See text for discussion.

(3) perpendicular to the active channel floodway but not the low-flow channel (e.g., cross sections B-B' at both times and C-C' at Time 2), or (4) not perpendicular to either the low-flow or active channel floodways (e.g., cross section A-A' at Time 2). For the purposes of this study, it was assumed that the orientation of cross sections relative to the active channel floodway remained constant throughout the monitoring period.

The second scaling adjustment was undertaken to compare among cross sections of different widths. Cross section plots were scaled by active channel floodway width by dividing the x-coordinate values by $L'_{eff}$ (Figure 9.14). This scaling had the effect of converting all x-coordinate values from meters to a fraction of the channel floodway width. This allowed visual classification of cross section responses (described in Section 9.7.1) that could be compared between sites (i.e., between channels of different sizes). The vertical dimension was not scaled. Scaling the vertical dimension would require estimation of the bankfull stage, which is a

highly subjective exercise in steep channels such as those at the Mack Creek and Cold Creek sites.

## 9.5   Other Data Preparation

All cross sections at each site were tied together in 3-dimensional space using the end point surveys, longitudinal profiles and maps (Figures 9.3, 9.5, 9.6, and 9.8). Survey data (see Section 9.3) were entered into an Excel spreadsheet for processing, where the measured horizontal and vertical distances and compass bearings were used to calculate x, y, and z coordinates relative to an arbitrary reference point using standard trigonometric relationships. The axes were aligned with the cardinal directions such that the +x direction is to the east, +y is to the north, and +z is vertically upward.

Particle size data from pebble counts conducted in conjunction with cross section surveys in 1995 and subsequent years were entered into a spreadsheet. For each year, summary statistics such as $D_{50}$ (the median particle diameter) and $D_{84}$ (the diameter which is greater than or equal to 84% of all particles in the sample) were calculated for each cross section and for each reach as a whole (pooling all samples). $D_{84}$ is a commonly used statistic in fluvial hydraulic and sediment transport calculations and is often used to characterize bed roughness (e.g., Bathurst, 1978; Thorne and Zevenbergen, 1985; Grant et al., 1990).

## 9.6   Peak Flow Analysis

### 9.6.1   DETERMINATION OF HISTORICAL PEAK FLOWS AT THE CROSS SECTION SITES

For each pair of consecutive cross section profile surveys (Table 9.2), channel adjustments inferred from the profile plots were assumed to be associated with the largest peak flow event that occurred during the interval between surveys. Since significant change is infrequent in this system and there are seldom multiple potentially channel-modifying events in any given year, it is reasonable as a first

approximation to assume that any observed changes are associated with the largest peak flow event during the interval between consecutive surveys. The simplest and perhaps the most relevant measure of the magnitude or intensity of peak flow events for this purpose is the instantaneous peak discharge, which is readily available from stream gaging data.

The LOL site and the Mack Creek sites are fortunate to be located close to stream gages for which data are available over the entire length of the cross section record (Figure 3.1). For these study reaches, the gaging station data were assumed to accurately represent the hydrologic conditions experienced within the reach. For the MAC and LOL sites, the measured discharges at the Mack Creek and the Lookout Creek gages, respectively, were adjusted for the small difference in drainage area between the gage location and the study reach. For the MCC site, data from the Mack Creek gage (which is located at the upper end of the study reach) were used without area adjustment.

Peak discharges at the middle Lookout Creek and Cold Creek sites are less well known, because neither channel has a gage near the study reach (Figure 3.1). For these sites, proxy data based on the unit area discharge (discharge divided by drainage area) were obtained from the nearest or most comparable available stream gages. The unit area discharge from the Lookout Creek gage was used for the middle Lookout Creek site, which is located on 4th-order Lookout Creek roughly in the center of the watershed (Figure 3.1) and has a drainage area approximately one-half that of the lower Lookout Creek site (Table 9.1). The gage for WS 8 (Figure 3.1) was used as a discharge proxy for the Cold Creek study reach; WS 8 is roughly comparable to Cold Creek in drainage area and elevation (Tables 9.1 and 9.3). Although only 3 of the 5 stations (Lookout Creek, Mack Creek, and WS 8) were used directly to estimate flows at the cross section sites, discharge records for two additional "control" watersheds— WS 2 and WS 9—were also examined to assess the spatial variability of peak flow magnitudes. These stations were chosen because the watersheds they monitor (except for the Lookout Creek gage) are essentially undisturbed by logging, road-building or other land use activities.

9.6.2    FLOOD FREQUENCY ANALYSIS

Flood frequency analyses (Appendix D) were performed using data from the Lookout Creek, Mack Creek, and WS 8 gaging stations to estimate the frequency of peak flow events associated with channel changes observed at the cross section sites. Since the objective was to be able to relate cross section changes to the largest flood during the interval between consecutive (typically annual) surveys, the annual flood series (largest flood in each year) was used for this analysis rather than a partial duration series of all floods above a given threshold regardless of when they occur. Using an annual flood series also avoids the problem of having to decide whether closely spaced hydrograph peaks are independent events or not. Furthermore, the differences between recurrence intervals estimated using partial duration series and annual series are minor for the relatively infrequent events that are of greatest interest in this study (Haan, 1977).

Flood frequency analysis is a means of estimating, for any specified discharge $x$, the probability that this discharge will be equaled or exceeded within any given year—the *exceedance probability* of $x$. If the annual maximum discharge $X$ is thought of as a random variable with a cumulative distribution function (CDF) $F_X(x) = p_x$, where $p_x = \Pr\{X \leq x\}$, then the exceedance probability associated with a discharge of $x$ is $1-p_x$. The recurrence interval, or the expected average time interval between annual floods of magnitude $x$ or greater, is $RI_x = 1/(1-p_x)$ (Haan, 1977). For a series of $n$ annual maximum peak flow values, an empirical CDF can be constructed by plotting the magnitude of each event vs. its estimated exceedance probability. The remainder of the frequency analysis then consists of fitting a theoretical probability distribution function to the data.

The most commonly used estimator of exceedance probability, or plotting position as it is commonly called, is the Weibull plotting position, which is calculated as $m/(n+1)$, where $m$ is the rank of the event from 1 (largest) to $n$ (smallest) (Haan, 1977). The reciprocal of the plotting position for an event of magnitude $x$, or $(n+1)/m_x$, yields a point estimate of the recurrence interval $RI_x$ of $x$. The ranked annual peak flow values and the corresponding Weibull plotting positions and estimated

recurrence intervals for the annual maximum flood series for Lookout Creek, Mack Creek, and WS 8 are given in Appendix D, Table D.4.

The flood frequency analysis followed the procedure recommended by the U.S. Water Resources Council as described in Bulletin 17B (Interagency Advisory Committee on Water Data, 1982). The Bulletin 17B method involves fitting a Log Pearson Type III (LP III) distribution to the observed peak flow data using a modified method of moments (Stedinger et al., 1993). The method is described in detail in Bulletin 17B and in standard hydrology references, and is not repeated here. Summary statistics from the annual peak flow series and parameter values used in fitting the LP3 frequency curve to the data are given in Appendix D, Table D.5.

Two potential outliers were identified in the annual flood series for Lookout Creek. The peak flow for WY 1977—which at 293 cfs (8.30 $m^3$/s) was less than half as large as the next smallest annual peak flow in the data set—was identified as a low outlier (Appendix D) and was removed from the data prior to fitting the LP3 frequency distribution in accordance with the Bulletin 17B protocol. The February 1996 flood peak for Lookout Creek was slightly above the high outlier threshold (Appendix D, Table D.5). Lacking a sound basis for treating this value as an historic flood (i.e., as the largest flood in $N$ years, where $N$ is greater than the record length $n$ of measured flows), it was retained as part of the record as recommended in Bulletin 17B. No outliers were identified in the records for Mack Creek or WS 8.

## 9.7    Cross Section Change Analysis

The cross section data were analyzed using descriptive, semi-quantitative, and quantitative approaches. Descriptive methods (Section 8.3, Figure 8.4) were used to characterize channel response to different events and to address questions relating to between-site differences in the nature of channel response to a particular event, or between-event differences in the style of channel response at a site. A semi-quantitative, classification-based approach was used to answer questions pertaining to when detectable change in the channel cross-section profiles occurred and the frequency with which changes of different magnitude (minor, moderate, or

substantial) occurred through time (Section 9.7.1). Classified cross section changes were used in conjunction with a logistic regression approach (Section 9.7.3) to assess the probability of channel adjustments of a given relative magnitude within each study reach relative to the magnitude of the largest flood during the interval between consecutive cross section surveys. In the quantitative approach (Section 9.7.2), cross section data were used to estimate the magnitude of scour and deposition at each profile location and relate this to the magnitude of imposed stress (e.g., peak discharge) during the interval between surveys.

### 9.7.1   SEMI-QUANTITATIVE ASSESSMENT OF CHANNEL RESPONSE

A visual classification-based approach was developed to summarize channel adjustments of various relative magnitudes at each cross section at the MAC, MCC, LOM, and the LOL sites. For a given cross section location, each pair of corrected, filtered, and scaled profiles from consecutive surveys (Table 9.2) represented one observation of channel change (or lack of change) at one location for one "event," which was assumed to correspond to the largest peak flow during the time interval between observations. These channel change observations were scored using the criteria shown in Table 9.4 (see Figure 9.16 for definition sketch). Examples of scored profile plots representing each of the four cases are presented in Figure 9.17. Response scores for each pair of consecutive surveys are tabulated for the LOL, LOM, MCC and MAC sites in Appendix E.

In Figure 9.17(a), the cross section response was negligible and was scored as 0. The pair of profiles in Figure 9.17(b) show scour over an interval of $\geq 0.1$ channel widths with an amplitude of approximately 0.2 m, which meets the minimum criteria for a score of 1 (Table 9.4). In Figure 9.17(c), scour of $\geq 0.2$ m over a distance of $>0.2$ channel widths is apparent, resulting in a score of 2. Figure 9.17(d) shows a typical example of a cross section response to the February 1996 flood, in which each of two large cross section changes meet one or both of the alternate criteria for a score of 3 (Table 9.4): a vertical change of bed elevation of $\geq 0.5$ m over a distance of 0.2 channel widths or a vertical change of 0.3 m over a distance of 0.4 channel widths.

Table 9.4. Classification criteria for cross section response scores. See Figure 9.16 for definition sketch.

| Score | Description | Criteria | | |
|-------|-------------|----------|---|---|
| 0 | No significant detectable change | | | |
| 1 | Minor change | $\Delta z \geq 0.2$ m | and | $x_{int} \geq 0.1\ L'_{eff}$, or |
| | | $\Delta z \geq 0.15$ m | and | $x_{int} \geq 0.2\ L'_{eff}$ |
| 2 | Moderate change | $\Delta z \geq 0.4$ m | and | $x_{int} \geq 0.1\ L'_{eff}$, or |
| | | $\Delta z \geq 0.2$ m | and | $x_{int} \geq 0.2\ L'_{eff}$ |
| 3 | Substantial change | $\Delta z \geq 0.5$ m | and | $x_{int} \geq 0.2\ L'_{eff}$, or |
| | | $\Delta z \geq 0.3$ m | and | $x_{int} \geq 0.4\ L'_{eff}$ |

[1] $\Delta z$ is the average vertical distance between the channel bed/bank elevation in the profiles being compared and $x_{int}$ is the fraction of the effective orthogonalized cross section length, $L'_{eff}$ (see Figure 9.14), occupied by the feature or features. No more than 2 features were combined to meet the length criterion.



Figure 9.16. Definition sketch for visual cross section profile change classification scheme in Table 9.4. $L'_{eff}$ is defined in Figure 9.14; $\Delta z$ is the average vertical displacement between profiles within a particular erosional or depositional feature (e.g., 1 and 2, respectively) of length $x_{int}$.

Figure 9.17. Examples of consecutive cross section profile pairs classified by degree of channel adjustment. (a) LOM site, XS 1, 1997-98; (b) LOL site, XS 11, 1990-95; (c) LOL site, XS 2, 1996-97; (d) MAC site, XS 3, 1995-96.

This classification scheme facilitates comparisons between the different study reaches despite the range of channel sizes represented. For example, scour to a depth of 20 cm across a 1-m width of channel would be relatively more significant at the MAC site, where it would represent approximately 10% of the average active channel floodway width, than it would be at the LOL site, where the same 1-m wide scour patch would represent only about 3.5% of the average channel floodway width. Scaling the cross section profiles by the active channel floodway width eliminates this disparity and allows visual classification of channel adjustments of comparable relative magnitude. However, the trade-off is that since the absolute horizontal resolution of the cross section profiles is the same at all sites—typically about 0.5 m—the resolution of the scaled profiles varies inversely with channel width. Thus, the Mack Creek profiles generally have fewer data points (hence, poorer resolution) than the Lookout Creek profiles, and the Cold Creek profiles have such poor resolution that they were excluded from this portion of the analysis.
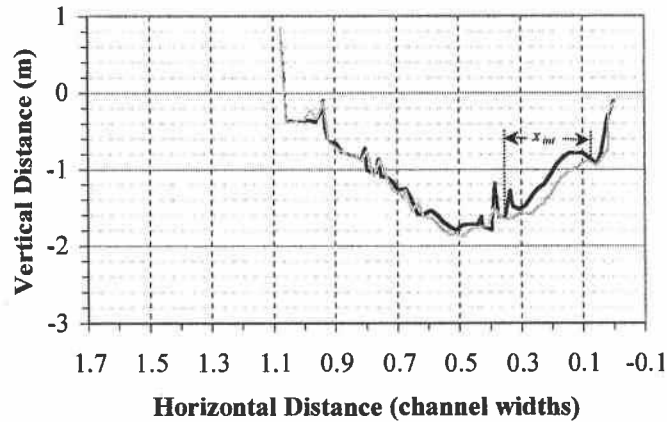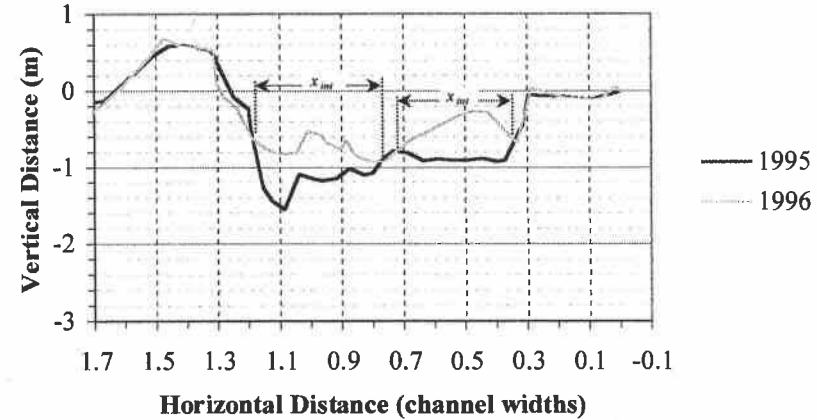
A cross section response score of 1 corresponds to the smallest change that could be identified with reasonable confidence across the range of cross section profile resolution (e.g., Figure 9.17b). These are very minor changes that probably would not be evident to an observer in the field. Changes associated with a response score of 2 are somewhat larger but still relatively modest (Figure 9.17c); changes at the low end of this class might only be noticeable to an observer who is very familiar with the site or is equipped with detailed photographs of the prior channel condition. Changes corresponding to a response score of 3 (e.g., Figure 9.17d) would be immediately apparent to an observer even casually familiar with the site.

Using the cross section response scores, a summary statistic was developed for each event which characterizes the relative magnitude of channel response at the reach scale. The *cross section response index* was defined as the sum of the response scores for all the cross sections at a site for a given event divided by the maximum possible score (3 times the number of cross sections). The cross section response index is distinct from the cross section response probability or proportion, $p$ (Section 9.7.3). By weighting larger responses (e.g., response score of 3) greater than small ones (e.g., response score of 1), the response index extracts more information from the classified

cross section responses (Appendix E) than does the response probability, $p$. The cross section response index is simply the arithmetic average of the individual cross section response scores at a site for a given event normalized by the maximum possible response score to yield a value between 0 and 1.

It is important to note that the cross section response index does not reflect the full range of possible cross section response. While a score of 0 indicates that essentially no detectable change occurred at any of the cross sections at a site, a score of 1 indicates only that all cross sections exhibited fairly substantial changes (i.e., they exceeded the criteria for a response score of 3; see Table 9.4); any larger changes are not reflected by the response index score. That is, while the response index can effectively quantify the overall relative magnitude of channel change as measured by the cross sections over a wide range, it cannot discriminate between events for which cross section changes substantially exceed the maximum cross section response score criteria for a significant proportion of the cross sections at a site. This is only an issue with respect to the February 1996 flood, for which many cross section changes greatly exceeded the classification criterion for the maximum response score of 3, especially at the Lookout Creek sites.

## 9.7.2 QUANTITATIVE ASSESSMENT OF CHANNEL RESPONSE

Cross section changes were quantified for the floods of February 1996 and February 1986, the two flood events which produced detectable change at the greatest number of cross sections at each site (Appendix E). The minimum magnitude of channel change during the interval between consecutive surveys was estimated for each cross section location from the cross section profile data. Where the more recent profile lies below the earlier profile, scour is indicated (e.g., feature 1 in Figure 9.16); where the reverse is true, deposition is indicated (e.g., feature 2 in Figure 9.16). The areas labeled 1 and 2 in Figure 9.16 each represent a volume of sediment per unit distance normal to the page (i.e., cubic meters of sediment per meter of channel length) that was eroded from or deposited in the channel, respectively, during the interval between surveys. The magnitude of the channel response can be characterized

by summing up all of the cross-sectional areas of scour and deposition across the channel. These are minimum values because the cross section profiles cannot detect areas of scour that were subsequently filled by new deposition or areas of deposition that were subsequently removed by channel scour during the interval between surveys.

Four measures of channel response were calculated for the 1986 and 1996 events (Appendix F). To facilitate comparison between study reaches, all values were scaled by the active channel floodway width, such that they can be thought of as representing an average depth of sediment eroded, deposited, or reworked. The four quantitative measures of channel response were:

1. mean scour depth—sum of cross sectional areas of scour divided by active channel floodway width,

2. mean fill depth—sum of cross sectional areas of deposition divided by active channel floodway width.

3. mean reworked depth—the sum of total scour and total deposition divided by active channel floodway width, and

4. net bed elevation change—total deposition minus total scour; divided by active channel floodway width; positive values indicate net deposition while negative values indicate net scour.

### 9.7.3 LOGISTIC REGRESSION ANALYSIS

Logistic regression was used to examine the relationship between cross section change (dependent variable) and applied stress (independent variable) over time at each reach. Logistic regression is a useful technique for analyzing the relationship between a binary or binomial response variable and one or more continuous and/or categorical explanatory variables (Ramsey and Schafer, 1997). The dependent variable was the proportion, $p$, of cross sections at a site exhibiting detectable change between consecutive surveys. It can be thought of either as the probability that a channel response will be observed for randomly selected cross section within the reach being tested (response probability) or as the proportion of the total reach length in which a channel response was observed. The independent variable was a measure of

the magnitude of the largest peak flow event during the interval between surveys, measured as unit area discharge, $Q^*$, or estimated recurrence interval, $RI$.

The logistic regression analysis was undertaken to answer two questions at each site:

1. How rapidly does $p$ increase with increasing event magnitude? Does the transition from low response probability (say, $p < 0.10$) to high response probability ($p > 0.90$) occur abruptly, over a narrow range of $Q^*$ or $RI$, (i.e., a threshold-like response, as in Figure 8.5, curve 1) or more gradually, over a wide range of $Q^*$ or $RI$ (e.g., Figure 8.5, curve 3)?

2. What magnitude of event $Q^*$ or return period $RI$ is the associated with a given response probability, $p$ (e.g., $Q_{50}$, Figure 8.5)?

The logistic regression analysis was also used to address two additional questions about similarities or differences between the cross section sites:

3. Are there significant differences between sites in the slope of the response curve (e.g., Figure 8.5, curve 1 vs. curve 2)?

4. Are there significant differences between sites in the event magnitude associated with a given response probability $p$ (e.g., the horizontal distance between curves 1 and 3 in Figure 8.5 for any specified value of $p$)?


### 9.7.3.1 Logistic Regression Theory and Model

If $m$ binary responses are a random sample from a population of binary responses with population proportion $p$, then their sum $Y$ has the *binomial($m,p$)* probability distribution (Ramsey and Shafer, 1997). The classified individual cross section responses in this study can be treated as binary variables, taking on values of one (changed) or zero (unchanged). Then for each cross section site, the sum $y_i$ of the $m_i$ binary cross section responses for the $i$th pair of consecutive survey dates can be treated as one realization of a random variable $Y_i$ drawn from a binomial($m_i, p_i$) distribution, where $p_i = Y_i/m_i$ is the unknown population proportion of 1's among the binary responses of a hypothetical population of potential cross sections at the site, and the observed sample proportion $p_i' = y_i/m_i$ is our estimate of the population

proportion. (Note that $p_i$ and $p_i'$ are also the population and sample means, respectively, of the binary responses).

A generalized linear model (GLM) is a probability model in which some function g of the mean $\eta$ of the response variable $Y$ is estimated as a linear function of a set of values $\mathbf{x} = \{x_1, x_2, ..., x_k\}$ of some set of explanatory variables $\{X_1, X_2, ..., X_k\}$. This can be written as

$$g(E(Y|\mathbf{x}) = g(\mu|\mathbf{x}) = \beta_0 + \beta_1 X_1 + ... + \beta_k X_k = \eta(\mathbf{x}) \qquad (9.1)$$

where g is known as the *link* function and $\eta(\mathbf{x})$ is called the *linear predictor* (MathSoft, 1997a). In the case of logistic regression, the link function is the *logit* function:

$$g(p) = \text{logit}(p) = \ln\left(\frac{p}{1-p}\right) \qquad (9.2)$$

In a logistic regression context, the mean of the binary responses is commonly designated by $p$ or $\pi$ rather than $\mu$ to emphasize that it is a probability or proportion. In our case, it is the binomial proportion $p_i = Y_i/m_i$ , not the individual binary responses, that constitute the response variable of interest. For each cross section site, the sample size $n$ is the number of pairs of consecutive survey dates (i.e., the number of survey dates minus one, see Appendix E), *not* the binomial denominator $m_i$.

The statistical package S-Plus (MathSoft, 1997b) was used to perform the logistic regression analysis. In S-Plus, a logistic regression is specified as a GLM (Equation 9.1) with the logit function (Equation 9.2) as the link function and a variance function defined by

$$\text{Var}(Y) = \phi m p(1 - p) \qquad (9.3)$$

[or equivalently, $\text{Var}(Y/m) = \phi p(1-p)$], where $\phi$ is a *dispersion parameter* that for logistic regression is typically set to be 1. S-Plus solves the GLM using the method of maximum likelihood estimation to estimate the values of the parameters $\beta_j$ in accordance with standard statistical theory (e.g., McCullagh and Nelder, 1989). Setting the dispersion parameter $\phi = 1$ is equivalent to assuming $Y$ is binomially

distributed. This assumption can be relaxed somewhat allowing $\phi$ to vary to account for under- or over-dispersion of the data relative to a binomial distribution, an approach known as quasi-likelihood estimation. The quasi-likelihood approach was used in this analysis.

The logit function is also known as the log-odds function, because the term on the right-hand side of Equation 9.2 is the natural logarithm of the odds of a "yes" result (observing change) vs. a "no" result (observing no change) in a single binary response (Ramsey and Shafer, 1997). For example, if 4 out of a sample of 10 cross sections exhibited detectable change, $y_i$ would be 4, $m_i$ would be 10, and hence the estimated probability of observing change at any single section, $p_i'$, would be 0.4. (The prime notation is used here to distinguish observed sample proportion $p_i'$ from the unknown population proportion $p_i$). However, the estimated *odds* of observing a change would be 2:3 ($p_i'/[1-p_i']$, or 0.4/0.6). That is, a cross section selected at random from the sample would be two-thirds as likely to exhibit detectable change as not, or conversely, it would be 50% more likely (odds of 3:2) *not* to show detectable change as to show such change. Note that *odds* are a ratio of the probabilities of two possible outcomes (change vs. no change), which is different from the *probability* of a particular outcome, which is given by the binomial proportion $y_i/m_i$, or 0.4 in this example. The probability of an outcome can range between 0 and 1, while the odds of that outcome can vary between 0 and infinity.

The relationship between probability or proportion and odds is illustrated in Figure 9.18, which shows $p$ as a function of the linear predictor $\eta$. If logit($p$) = $\eta$ (as in Equation 9.1 when the link function $g$ is the logit function), then

$$p = e^{\eta}/(1+e^{\eta}) \tag{9.4}$$

This is the logistic function, which is the inverse of the logit function and is the form of the predictions from a logistic regression model back-transformed to the scale response variable $Y/m$. For a unit increase in $\eta$ from $\eta_1$ to $\eta_2$, the odds increase by a fixed factor of $e$ (i.e., approximately 2.718), but $p$ increases by different amounts depending on the values of $\eta_1$ and $\eta_2$. More generally, for a change in $\eta$ of any fixed increment $\delta$, the odds will change by $e^{\delta}$. Hence, for a change $\Delta x$ in the value of a
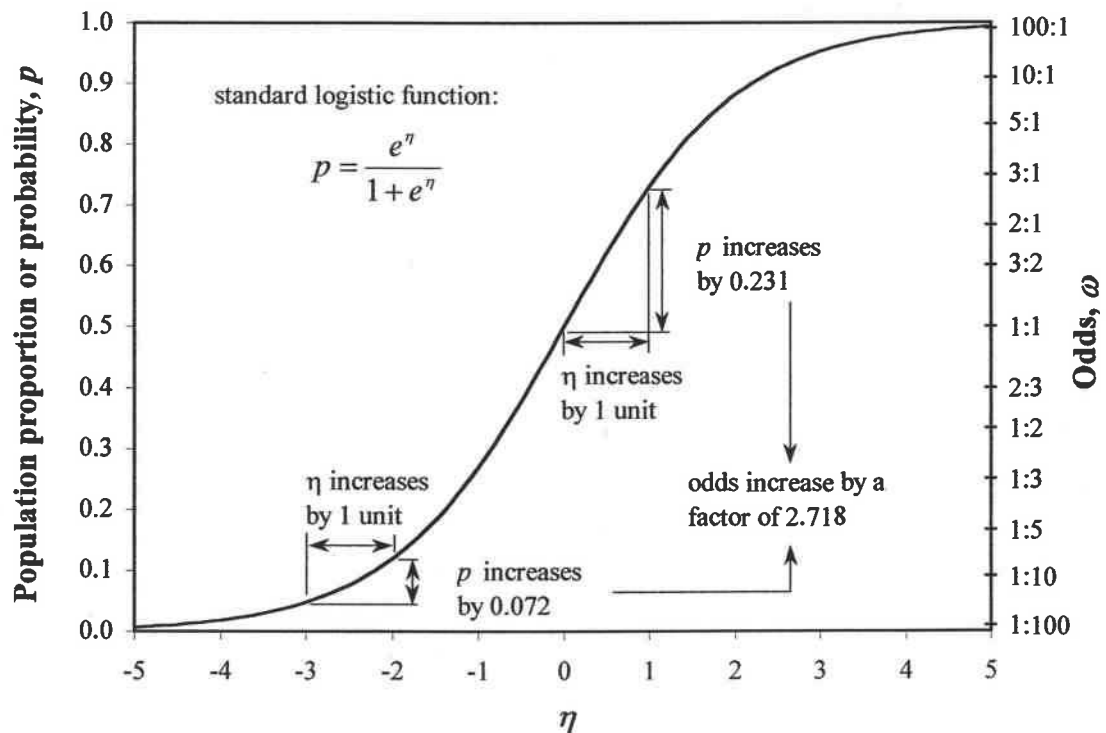
Figure 9.18. The standard logistic function and the relation between the probability and odds for an event occurring. The logistic function is the inverse of the logit function and gives the probability $p$ of an event as a function of the value of the linear predictor $\eta$ in a logistic regression model. The odds, $\omega$, are the ratio of the probability $p$ that an event will occur to the probatility $1-p$ that it will not occur. (Modified from Ramsey and Shafer [1997].)

single explanatory variable $X_j$ while holding all other explanatory variables constant in Equation 9.1 (for $1 \leq j \leq k$), $\eta$ would change by $\delta = \beta_j X_j$ and the odds would change by $e^{\delta} = e^{\beta_j \Delta x}$. The quantity $e^{\beta_j \Delta x}$ is the known as *odds ratio* associated with a change $\Delta x$ in the explanatory variable $X_j$. Note that the odds ratio would be greater than 1 (i.e., an increase) for $\delta > 0$ and less than one (a decrease) for $\delta < 0$.

A simple logistic regression model to relate response probability $p$ to a single response variable, say $Q^*$, can be expressed as

$$\text{logit}(Y/m) = \beta_0 + \beta_1 Q^*_1 \tag{9.5}$$

The regression parameters in this model relate explicitly to the conceptual model of Section 8.4 and the questions of interest set forth at the beginning of this section.

Figure 8.5 shows several hypothetical channel response curves which could be modeled by Equation 9.5. The slope parameter $\beta_1$ in this model characterizes the shape of the response curve, with low values corresponding to a gradual response (curve 3 in Figure 8.5) and high values corresponding to an abrupt or threshold-like response (curves 1 and 4 in Figure 8.5). (Also, as discussed above, $\beta_1$ gives the multiplicative increase in the odds of observing change for a unit increase in $Q^*$).

The position of the response curve on the horizontal axis in Figure 8.5 is a function of both the slope and intercept parameters ($\beta_1$ and $\beta_0$, respectively) in Equation 9.5. Specifically, the value of $Q^*$ associated with a 50% change probability, $Q^*_{50}$, is equal to $-\beta_0/\beta_1$. To see this, note that when $p_i = Y_i/m_i = 0.5$, the left-hand side of Equation 9.5 becomes zero (because logit(0.5) = ln [0.5/(1-0.5)] = ln 1 = 0). Then solving for $Q^*$ yields $-\beta_0/\beta_1$. In Figure 8.5, curves 1 and 4 have the same value of $\beta_1$ but different values of $\beta_0$ (such that $-\beta_0/\beta_1$ for curve 4 is greater than for curve 1), while curves 1 and 2 have different values of $\beta_1$, but the ratio of the two parameters ($\beta_0/\beta_1$) is the same.

For purposes of comparing responses between two sites, it is more useful to formulate the logistic regression model as

$$\text{logit}(Y/m) = \beta_0 + \beta_1 Q^*_i + \beta_2 Site + \beta_3 Q^*_i \times Site \qquad (9.6)$$

where $Site$ is an indicator variable taking on the values 0 for one site (the *reference site*) or 1 for the other site. The slope and intercept parameters for the reference site are the same as for the single-site model, $\beta_1$ and $\beta_0$ respectively, while the corresponding parameters for the second site are given by $\beta_1 + \beta_3$ and $\beta_0 + \beta_2$, respectively. $\beta_2$ and $\beta_3$ are *site contrast* parameters and measure the between-site differences in the slope and intercept parameters, respectively. $\beta_2$ by itself has no useful interpretation. However, $\beta_3$ is a measure of the degree to which one site exhibits a more threshold-like response than the other (e.g., the difference between curves 1 and 2 in Figure 8.5). A test whether the response curves for the two sites are significantly different in this regard is equivalent to a test of the hypothesis that $\beta_3 = 0$.

It is not possible to formulate a test for whether $Q^*_p$ differs between sites in terms of a hypothesis about a single model parameter, since this difference depends upon both slope and intercept parameters as well as the value of $p$. However, S-Plus does calculate a standard error for the predicted values of $p$ from the logistic regression, allowing the calculation of an approximate 95% confidence interval ($\pm$ 2 standard errors) for the predicted response curve. For those values of $p$ for which the predicted response curves for two sites lie outside each other's 95% confidence bands, the difference in $Q^*_p$ values can be inferred to be statistically significant at an approximate significance level of 0.05 or less.

### 9.7.3.2 Model Assumptions

The logistic regression approach used here has the following built-in assumptions:

1. the cross sections at each site comprise a representative random sample of potential cross sections at that site;
2. the probability $p$ corresponding to any given value of $Q^*$ is constant through time (i.e., stationary); and
3. the cross section responses are independent of each other.

As is common in statistical analyses of real-world data, none of these assumptions are strictly true, so the question with respect to the validity of the approach becomes one of how serious are the violations, and how does this affect the interpretation of the results? The consequences of violating the first assumption are serious only if the cross section locations used for a given site are biased or otherwise unrepresentative of the reach as a whole, which is not believed to be the case. The second assumption is relevant to a question posed in this study—whether channel sensitivity to disturbance changes over time, particularly in the aftermath of a major flood. Because past disturbances set the antecedent conditions for future disturbances, it is important to check this assumption. Of particular interest is whether there are any trends through time in the relationship between $Q^*$ and cross section response as measured by either $p$ or the cross section response index. The residuals from a
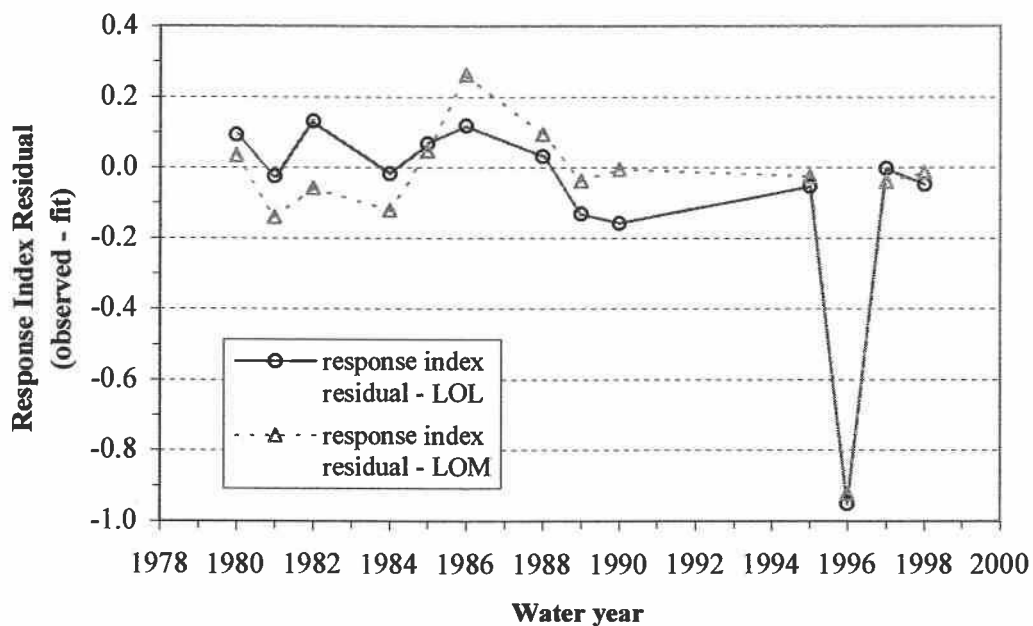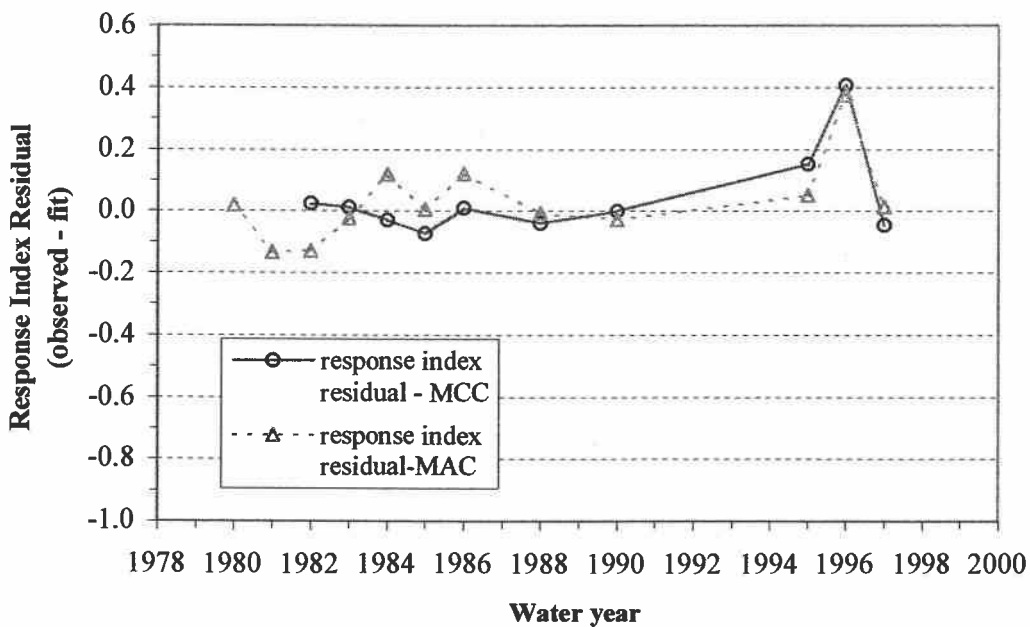
**(a) Lookout Creek sites**



**(b) Mack Creek sites**



Figure 9.19. Residuals from regression of cross section response index scores vs. $Q^*$ plotted by water year: (a) Lookout Creek sites, and (b) Mack Creek sites. The 1996 flood was omitted from the regression model.

regression of cross section response index vs. $Q^*$ shows no sign of a trend over time for any of the cross section sites (Figure 9.19), suggesting that the assumption of stationarity is valid.

Lack of independence (assumption no. 3) is the issue of greatest concern in this analysis. Cross section responses are clearly spatially correlated for large events such as the 1996 flood, where reach scale channel responses were observed, at least at the Lookout Creek sites (see Sections 10.2.3 and 10.2.4). However, spatial autocorrelation is much less of an issue with respect to cross section responses to the smaller events which make up the bulk of the data set. Use of the quasi-likelihood approach also helps mitigate potential effects of lack of independence between cross sections.